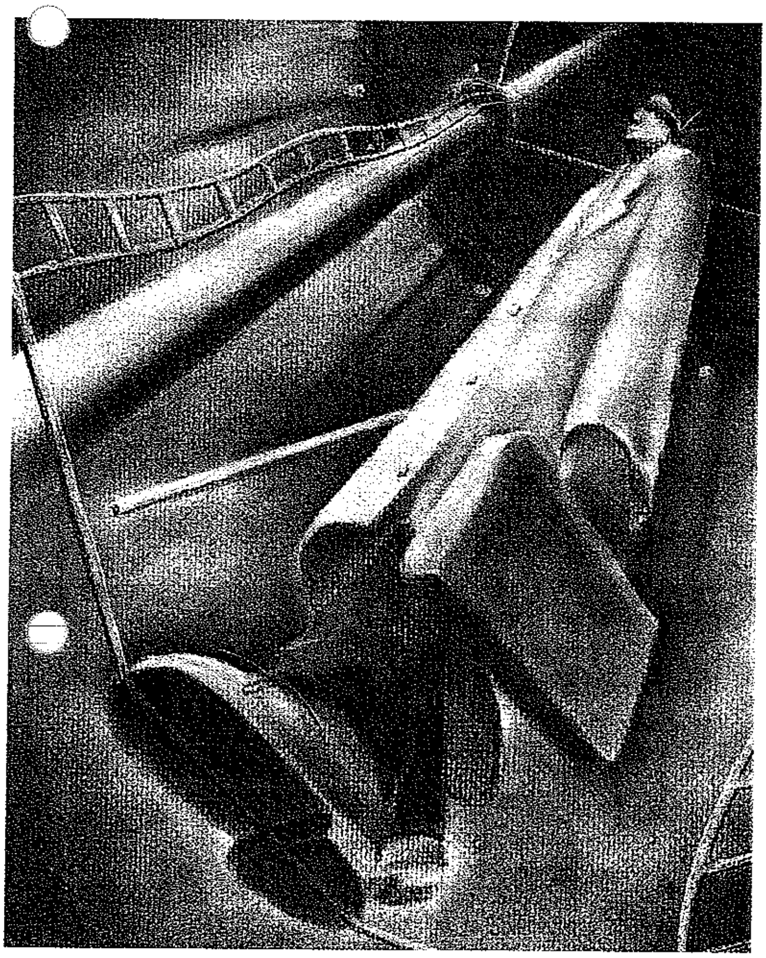
A balanced view



There's a multitude of balanced line input topologies to choose from. Here, Douglas Self looks at a selection of the more useful ones, and explains where and how they should be applied.

There are only two kinds of input stage – unbalanced and balanced. For interconnection this is the primary distinction. Apart from balancing requirements, a line-level input, as opposed to a microphone input, is expected to have a reasonably high impedance to allow multiple connections to a single output.

Traditionally, a 'bridging impedance' – ie high enough to put negligible loading on historical 600Ω lines – was 10kΩ minimum. This is still appropriate for modern low-impedance outputs. However, a higher impedance of 100kΩ or even more is desirable for interfacing to obsolete valve equipment, to avoid increased distortion and curtailed headroom.

Another common requirement is true variable gain at the balanced input, as putting the gain control further down the signal path means that it is impossible to prevent input amplifier overload. Thus you need a balanced stage that can attenuate as well as amplify, and this is where the circuit design starts to get interesting.

In the following circuitry, small capacitors often shunt the feedback elements to define bandwidth or ensure stability. These are omitted for clarity.

Unbalanced inputs. These are straightforward; variable-gain series-feedback stages are easily configured as in **Fig. 1**, providing a minimum gain of unity is acceptable; R_2 sets the gain law in the middle of the pot travel.

It is also simple to make a stage that attenuates as well as amplifies. But this implies a shunt-feedback configuration as in **Fig. 2**, with a variable input impedance. The minimum input impedance R_1 cannot be much higher than 10kΩ or resistor noise becomes excessive.

For a series-feedback stage, the input impedance can be made as high as desired by bootstrapping; an input resistance of 500kΩ or greater is perfectly possible. This does *not* imply a poorer noise performance, as the noise depends on the source resistance and semi-

Table 1. Differential amplifier input impedances.

Case	Conditions	Hot i/p Z	Cold i/p Z
1	Hot only driven	20kΩ	Grounded
2	Cold only driven	Grounded	10kΩ
3	Both driven balanced	20kΩ	6.7kΩ
4	Both driven cm, ie together	20kΩ	20kΩ
5	Both driven floating	10kΩ	10kΩ

conductor characteristics.

To ram the point home, my own personal best is 1GΩ, in a capacitor microphone head amplifier. Although the input impedance is many orders of magnitude greater than the 1 to 2kΩ of a dynamic microphone preamp, the E_{IN} is −110dBu, ie only 18dB worse.

Naturally, any unbalanced input can be made balanced or floating by adding a transformer.

Balanced inputs. A standard one-op-amp differential input stage is shown in **Fig. 3**. Unlike instrumentation work, a super-high cmrr is normally unnecessary. Ordinary 1% resistors and no trimming will not give cmrr better than 45dB; however this is usually adequate for even high-quality audio work.

It is never acceptable to leave either input floating. This causes serious deterioration of noise, hum etc. Grounding the cold input locally to create an unbalanced input is quite alright, though naturally all the balanced noise rejection is lost.

The hot input can be locally grounded instead. In this case, the cold input is driven, to create a phase-inverting input that corrects a phase error elsewhere, but this is not good practice: the right thing to do is to sort out the original phase error.

Balanced input technologies

There are many, many ways to make balanced or differential input amplifiers, and only the most important in audio are considered. These are:

- The standard differential amplifier
- Switched-gain balanced amp.
- Variable-gain balanced amp.
- The 'Superbal' amp.
- Hi-Z balanced amp.
- Microphone preamp plus attenuator
- Instrumentation amp.

Standard differential amplifier. The standard one-op-amp differential amplifier is a very familiar circuit block, but its operation often appears somewhat mysterious. The version in Fig. 3 has a gain of R_3/R_1. $(=R_4/R_2)$ It appears to present inherently unequal input impedances to the line; this has often been commented on[1] and some confusion has resulted.

The root of the problem is that a simple differential amplifier has interaction between the two inputs, so that the input impedance on the cold input depends strongly on the signal applied to the hot input. Since the only way to measure input impedance is to apply a signal and see how much current flows into the input, it follows that the apparent input impedance on each leg varies according to the way the inputs are driven. If the amplifier is made with four 10kΩ resistors, then the input impedances Z are as in **Table 1**.

Some of these impedances are not exactly what you would expect. In Case 3, where the input is driven as from a transformer with its centre-tap grounded, the unequal input impedances are often claimed to 'unbalance the line'. However, since it is common-mode interference we are trying to reject, the cm impedance is what counts, and this is the same for both inputs.

The vital point is that the line output amplifier will have output impedances of 100Ω or less, completely dominating the line impedance. These input impedance imbalances are therefore of little significance in practice; audio connections are not transmission lines (unless they are telephone circuits several miles long) so the input impedances do not have to provide a matched and balanced termination.

As the first thing the signal encounters is a 10kΩ series resistor, the low impedance of 6.7kΩ on the cold input sounds impossible. But the crucial point is that the hot input is driven simultaneously. As a result, the inverting op-amp input is moving in the opposite direction to the cold input, due to negative feedback, a sort of anti-bootstrapping that reduces the effective value of the 10kΩ resistor to 6.7kΩ.

The input impedances in this mode can be made equal by manipulating resistor values, but this makes the cm impedances (to ground) unequal, which seems more undesirable.

In Case 5, where the input is driven as from a floating transformer with any centre-tap unconnected, the impedances are nice and equal. They must be, because with a floating winding the same current must flow into each input. However, in this connection the line voltages are *not* equal and opposite: with a true floating transformer winding the hot input has all the signal voltage on it while the cold has none at all, due to the internal coupling of the balanced input amplifier.

This seemed very strange when it emerged from simulation, but a reality-check proved it true. The line has been completely unbalanced as regards talking to other lines, although its own common-mode rejection remains good.

Even if perfectly matched resistors are assumed, the common-mode rejection ratio of this stage is not infinite; with a *TL072* it is about −90dB, degrading from 100Hz upwards, due to the limited open-loop gain of the op-amp.

Switched-gain balanced amplifier. The need for a balanced input stage with two switched gains crops up frequently. The classic application is a mixing desk to give optimum performance with both semi-professional (−7.8dBu) and professional (+4dBu) interface levels.

Since the nominal internal level of a mixer is usually in the range −4 to 0dBu, the stage must be able to switch between amplifying and attenuating, maintaining good cmrr in both modes.

The obvious way to change gain is to switch both $R_{3,4}$ in Fig. 3, but a neater technique is shown in **Fig. 4**. Perhaps surprisingly, the gain of a differential amplifier can be manipulating by changing the drive to the feedback arm (R_3 etc) only, without affecting the cmrr. The vital

Table 2.

	Capacitive 1mA	CMRR
Conventional	−20dBv	−46dB
Impedance-bal 99Ω	−60dBv	−101dB
Impedance-bal 100R	∞	−85dB
Impedance-bal 101R	−60dBv	−79dB

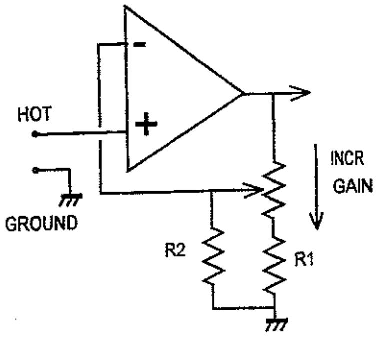


Fig. 1. variable-gain series-feedback unbalanced input stage. Resistor R_2 sets mid-position gain.

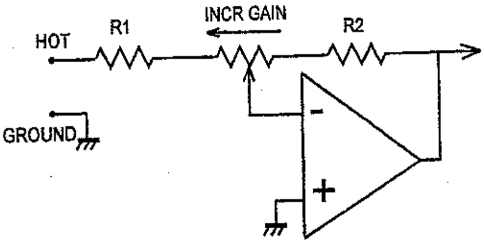


Fig. 2. Shunt-feedback configuration, with a low and variable input impedance.

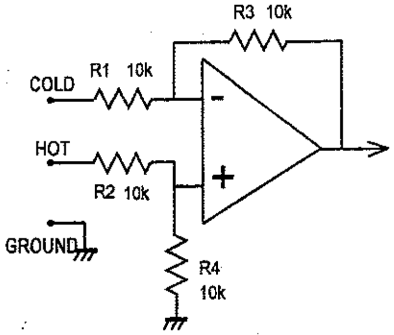


Fig. 3. Standard one-op-amp differential amplifier, arranged for unity gain.

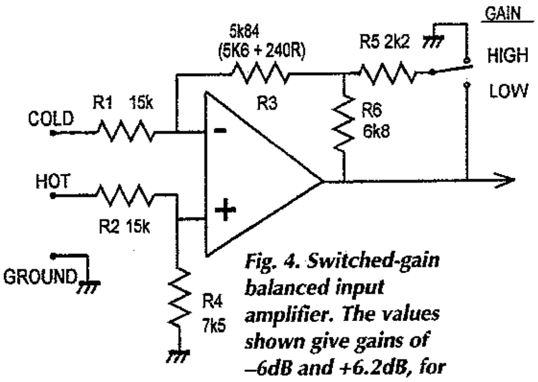


Fig. 4. Switched-gain balanced input amplifier. The values shown give gains of −6dB and +6.2dB, for switching between pro and semi-pro interface levels.

tion of ground noise (cmrr=unity) or electrostatic crosstalk; in the latter case the 1mA notional crosstalk signal yields a –20dBv signal as the impedance to ground is very nearly 100Ω.

Unbalanced output to balanced input. Assuming the output ground is connected to the cold-line input, then in theory there is complete cancellation of ground voltages. This is true, *unless* the output has a series output resistor to buffer it from cable capacitance, – which is almost always the case – for this will unbalance the line.

If the output resistance is 100Ω, and the cold line is simply grounded as in Fig. 8a, then R_s degrades the cmrr to –46dB even if the balanced input has exactly matched resistors.

The impedances on each line will be different, but not due to the asymmetrical input impedances of a simple differential amplifier; hot line impedance is dominated by the output resistance R_s on the hot terminal (100Ω) and the cold line impedance is zero as it is grounded at the output end. The rejection of capacitive crosstalk therefore depends on the unbalanced output impedance. It will be no better than for an unbalanced input, as for the unbalanced output to balanced input case. The main benefit of this connection is ground noise rejection, which solves the most common system problem.

Impedance-balance out to unbalanced in. There is nothing to connect the output cold terminal to at the input end, and so this is the same as the ordinary unbalanced connection for the **unbalanced output to balanced input** configuration.

Impedance-balance out to balanced in. In theory there is complete cancellation of both capacitive crosstalk and common-mode ground voltages, as the line impedances are now exactly equal.

Table 2 shows the improvement that impedance-balancing offers over a conventional unbalanced output, when driving a balanced input with exactly matched resistors.

The effect of tolerances in the impedance-balance resistor are also shown; the rejection of capacitive crosstalk degrades as soon as the value moves away from the theoretical 100Ω, but the cmrr actually has its point of perfect cancellation slightly displaced to about 98.5Ω, due to second-order effects. This is of no consequence in practice.

Ground-cancelling out to unbalanced in. There is complete cancellation of ground voltages, assuming the ground-cancel output has an accurate unity gain between its cold and hot terminals. This is a matter for the manufacturer.

Ground-cancelling in this way is a very efficient and cost-effective method of interconnection for all levels of equipment, but tends to be more common at the budget end of the market.

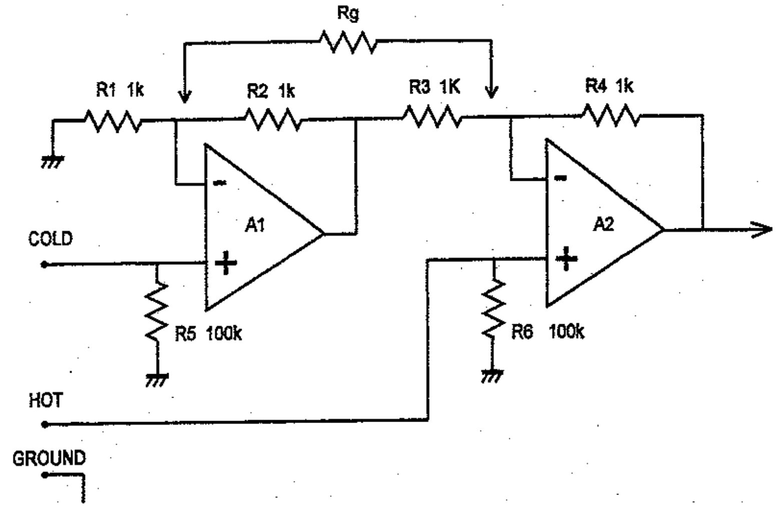


Fig. 7. High-impedance balanced input stage; R_5 and R_6 set input impedance, and can be much higher. Add R_g to increase gain.

Ground-cancelling out to balanced in. This combination needs a little thought. At first there appears to be a danger that the ground-noise voltage might be subtracted twice, which will of course be equivalent to putting it back in in anti-phase, gaining us nothing.

In fact this is not the case, though the cancellation accuracy is compromised compared with the impedance-balanced case; the common-mode rejection will not exceed 46dB, even with perfect resistor matching throughout. Capacitive crosstalk is no better than for the 'Unbalanced output to balanced input' ie approximately –21dB, which means virtually no rejection. However, this is rarely a problem in practice.

Balanced output to unbalanced input. This is not a balanced interconnection. There is nowhere to connect the balanced cold output to; it must be left open-circuit, its signal unused, so there is a 6dB loss of headroom in the link. The unbalanced input means the connection is unbalanced, and so there is no noise rejection.

Balanced out to balanced in. A standard balanced system, that should give good rejection of ground noise and electrostatic crosstalk.

Quasi-floating out to unbalanced in. Since the input is unbalanced, it is necessary to ground the cold side of the quasi-floating output. If this is done at the remote (input) end then the ground voltage drop is transferred to the hot output by the quasi-floating action, and the ground noise is cancelled in much the same way as a ground-cancelling output.

However, in some cases this ground connection must be local, ie at the output end of the cable, if doing it at the remote (input) end causes high-frequency instability in the quasi-floating output stage. This may happen with very long cables. Such local grounding rules out rejection of ground noise because there is no sensing of the ground voltage drop.

Perhaps the major disadvantage of quasi-floating outputs is the confusion they can cause. Even experienced engineers are liable to mistake them for balanced outputs, and so leave the cold terminal unconnected. This is not a good idea. Even if there are no problems with pickup of external interference on the unterminated cold output, this will cause a serious increase in internal noise. I believe it should be standard practice for such outputs to clearly marked as what they are.

Quasi-floating out to balanced in. A standard balanced system, that should give good rejection of ground noise and electrostatic crosstalk.

The hot and cold output impedances are equal, and dominate the line impedance, so even if the line input impedances are unbalanced, there should also be good rejection of electrostatic crosstalk.

Wiring philosophies

It has been assumed above that the ground wire is connected at both ends. This can cause various difficulties due to ground currents flowing through it.

For this reason some sound installations have relied on breaking the ground continuity at one end of each cable. This is called the one-end-only, or oeo, rule.[4] It prevents ground currents flowing but usually leaves the system much more susceptible to rf demodulation. This is because the cable screen is floating at one end, and is now effectively a long antenna for ambient rf.

There is also the difficulty that non-standard cables are required. A consistent rule as to which end of the cable has no ground connection must be enforced. The oeo approach may be workable for a fixed installation that is rarely modified, but for touring sound reinforcement applications it is unworkable.

A compromise that has been found acceptable in some fixed installations is the use of 10nF capacitors to ground the open screen end at rf only; however, the other problems remain.

The formal oeo approach must not be confused with 'lifting the ground' to cure a

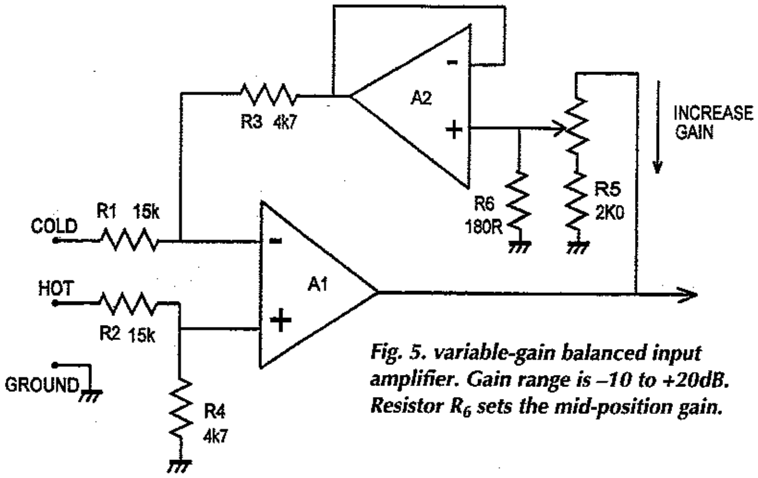


Fig. 5. variable-gain balanced input amplifier. Gain range is –10 to +20dB. Resistor R_6 sets the mid-position gain.

point is to keep the resistance of this arm the same, but drive it from a scaled version of the op-amp output.

Figure 4 uses the network $R_{5,6}$, which has the same 2kΩ output impedance whether R_4 is switched to the output (low gain) or ground (high gain). For low gain, the feedback is not attenuated, but fed through $R_{5,6}$ in parallel.

For high gain, $R_{5,6}$ become a potential divider. Resistor R_3 is reduced by 2kΩ to allow for the $R_{5,6}$ output impedance. The stage can attenuate as well as amplify if R_1 is greater than R_3, as shown here. The nominal output of the stage is assumed to be –2 dBu; the two gains are –6.0 and +6.2 dB.

The differential input impedance is 11.25kΩ via the cold and 22.5kΩ via the hot input. Common mode input impedance is 22.5kΩ for both inputs.

Variable-gain balanced amplifier. A variable-gain balanced input should have its gain control at the very first stage, so overload can always be avoided. Unfortunately, making a variable-gain differential stage is not so easy; dual potentiometers can be used to vary two of the resistances, but this is clumsy and will give shocking cmrr due to pot mismatching. For a stereo input the resulting four-gang potentiometer is unattractive.

The gain-control principle is essentially the same as for the switched-gain amplifier above. To the best of my knowledge, I invented both stages in the late seventies, but so often you eventually find out that you have re-invented instead; any comments welcome.

Feedback arm R_3 is of constant resistance, and is driven by voltage-follower A_2. This eliminates the variations in source impedance at the potentiometer wiper, which would badly degrade cmrr. As in Fig. 1, R_6 modifies the gain law; however, the centre-detent gain may not be very accurate as it partly depends on the ratio of potentiometer track (often no better than ±10%, and sometimes worse) to 1% fixed resistors.

This stage is very useful as a general line input with an input sensitivity range of –20 to +10dBu. For a nominal output of 0dBu, the gain of **Fig. 5** is +20 to –10dB, with R_6 chosen for 0dB at the central wiper position.

An op-amp in a feedback path appears a dubious proposition for stability, but here, working as a voltage-follower, its bandwidth is maximised and in practice the circuit is dependably stable.

The 'Superbal' amplifier. This configuration[2] gives much better input symmetry than the standard differential amplifier, **Fig. 6.** The differential input impedance is exactly 10kΩ via both hot and cold inputs. Common mode input impedance is 20kΩ for both inputs. This configuration is less easy to modify for variable gain.

High-Z balanced amp. High-impedance balanced inputs, above 10kΩ, are useful for interfacing to valve equipment. Adding output cathode-followers to valve circuitry is expensive, and so the output is often taken directly from a gain-stage anode. Even a light loading of 10kΩ may seriously compromise distortion and available output swing.

All of the balanced stages dealt with up to now have their input impedances determined by the values of input resistors etc, and these cannot be raised without degrading noise performance. **Figure 7** shows one answer to this. The op-amp inputs have infinite impedance in audio terms, subject to the need for R,R to bias the non-inverting inputs.[3]

Adding R_g increases gain, but preserves balance. This configuration cannot be set to attenuate.

Microphone preamp with attenuator. It is often convenient to use a balanced microphone preamp as a line input by using a suitable balanced attenuator, typically 20 to 30dB. The input impedance of the microphone input stage will be 1 to 2kΩ for appropriate mic loading, and this constrains the resistor values possible.

Keeping the overall input impedance to at least 10kΩ means that the divider impedance must be fairly high, with a lot of Johnson noise. As a result, the total noise performance is almost always inferior to a dedicated balanced line-input amplifier. Common-mode rejection ratio is determined by the attenuator tolerances and will probably be much inferior to the basic microphone amp, which usually relies on inherent differential action rather than component matching.

Figure 8a shows a bad way to do it; the differential signal is attenuated, but not the common-mode, so cmrr is degraded even if the resistors are accurate. **Figure 8b** attenuates differential and common-mode signals by the same amount, so cmrr is preserved, or at any rate no worse than resistor tolerances make it.

Instrumentation amplifier. All the balanced inputs above depend on resistor matching to set the cmrr. In practice this means better than 45dB is not obtainable without trimming. If a cmrr higher than this is essential, an IC instrumentation amplifier is a possibility.

Common-mode rejection ratio can be in the range 80 to 110dB, without trimming or costly precision components. The IC tends to be expensive, due to low production volumes, and the gain is often limited in range and cannot usually be less than unity.

In audio work, cmrr of this order is rarely if ever required. If the interference is that serious, then it will be better to deal with the original source of the noise rather than its effects.

Input/output combinations

Taking five kinds of output – the rare case of floating output transformers being excluded – and the two kinds of input amplifier, there are ten possible combinations of connection. The discussion below assumes output R_s is 100Ω, and the differential input amplifier resistors R are all 10kΩ, as in Fig. 3.

Unbalanced output to unbalanced input. This is the basic connection. There is no rejec-

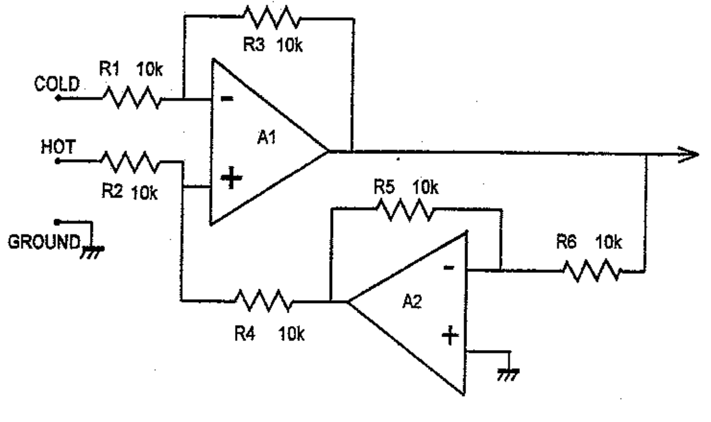


Fig. 6. The 'Superbal' balanced input stage; input impedance on hot and cold are equal for both differential and common mode.

ground loop. Unbalanced equipment sometimes provides a ground-lift switch that separates audio signal ground from chassis safety ground; while this can sometimes be effective, it is not as satisfactory as balanced connections. Lifting the ground must **never** be done by removing the chassis safety earth; this removes all protection against a live conductor contacting the case and so creates a serious hazard. It is also in many cases illegal.

The best approach therefore appears to be grounding at both ends of the cable, and relying on the cmrr of the balanced connection to render ground currents innocuous. Ground currents of 100mA appear to be fairly common; ground currents measured in amps have however been encountered in systems with serious errors.

A typical example is connecting incoming mains 'Earth' – which is actually 'Neutral' in many cases – to a technical ground such as a buried copper rod. Take a look the section headed 'Electrical Noise' in last month's article for more details.

Ground currents cause the worst problems when they flow not only through cable shields but also the internal signal wiring of equipment. For this reason the preferred practice is to terminate incoming ground wires to the chassis earth of the equipment. This keeps ground currents off pcbs, where the relatively high track resistances would cause bad common-impedance coupling, and preserves rf screening integrity.

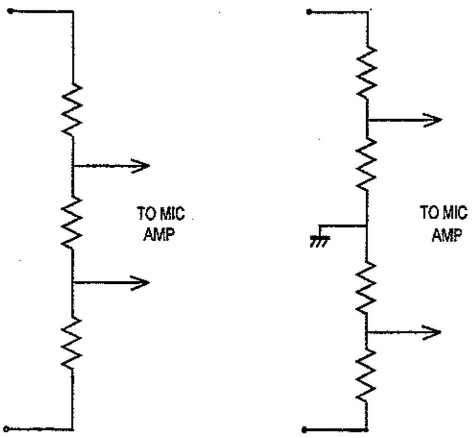


Fig. 8. At a), balanced attenuators convert a microphone preamp to line input. Circuit b) is superior as both differential and common-mode signals are equally attenuated, so common-mode rejection is not degraded more than necessary.

Grounding is simplified for source equipment that has no other connections, such as double-insulated compact-disc players. These carry a 'square-in-a-square' symbol to denote higher standards of mains insulation, so that external metalwork need not be grounded for safety. Such equipment often has unbalanced outputs, and can usually be connected directly to an unbalanced input with good results, as there is no path for any ground currents to circulate in.

If a balanced input is used, then connecting the hot input to cd signal and the cold to cd 'ground' leaves the cd player ground floating, and this will seriously degrade hum and rf rejection. The real ground must be linked to cd player common.

I think this article shows that balanced line interconnections are rather more complex than is immediately obvious. Having said that, with a little caution they work very well indeed. ■

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FARNELL LFP1 Sine/Sq Oscillator 10Hz-1MHz	£85
RACAL 9008 Automatic Mod Meter 1.5MHz-2GHz	£300
SAYROSA 252 Automatic Mod Meter 1.5MHz-1.2GHz	£150
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FARNELL L30-1 0-30 Volts; 0-1 Amp. Metered	£65
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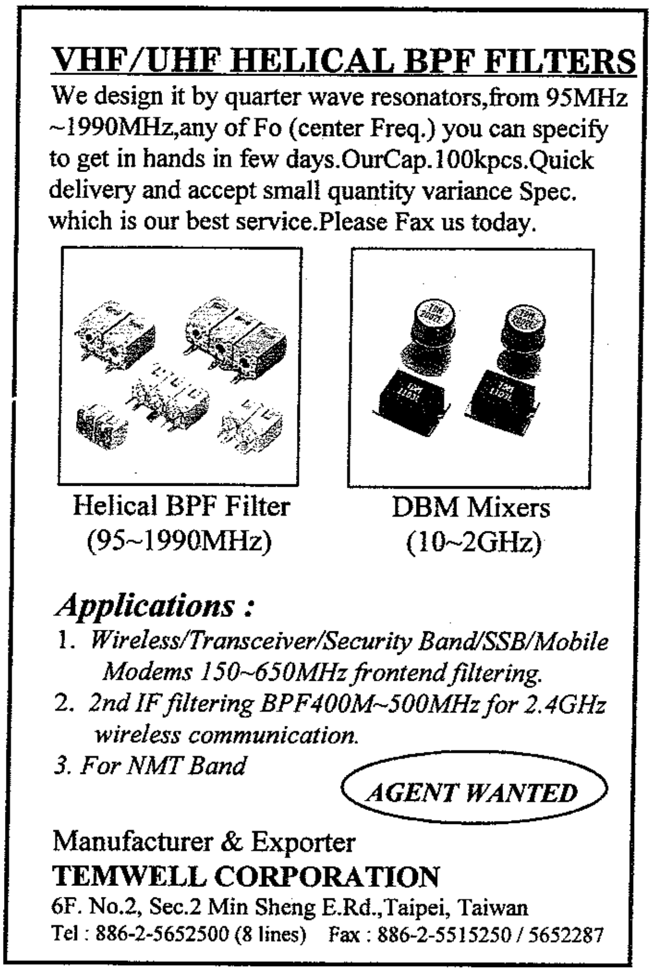

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