A Question of Balance

A fresh look at a frequently misunderstood topic — the use of balanced lines for audio signal connections.

By Barry Porter

It's well known that something called balancing is important in the world of professional audio, but not many people seem to know what the system does or what advantages it brings. If you fall into this category and would like to know a little more, read on.

The individual units of a domestic system, such as a preamplifier and a power amplifier, are usually connected together with a length of screened cable (Fig. 1). Signal is carried along the inner conductor, and the outer screen joins the ground lines of the electronics in the two items of equipment. This type of interconnection is termed 'unbalanced' and works well enough providing the cable is not of excessive length and does not pass near to a strong source of electrical interference. Although the screen layer gives some protection to the signal carrying conductor, a strong external AC field such as that surrounding an AC transformer will pass through the screen and add its unwanted modulation to the signal.

This problem is obviously at its greatest when the cable carries signals at a low level and is followed by lots of amplification. An example is the connection between a microphone and the input channel of a mixing console, where any hum and noise picked up by the cable may be amplified by as much as 60dB.

One way to minimize the effect of external hum and noise is to keep the line impedance as low as possible and the signal level as high as possible. If the sending amplifier has a very low output impedance — less than 1 ohm is possible with operational amplifiers — the connecting cable appears to be at about ground potential, and external fields will exert very little influence.

This principle works well for cable runs of less than 30 metres or so where the external field is not too intense, but when long interconnections are used, the resistance of the signal carrying wire becomes significant and the line impedance increases as you get further from the sending amplifier. In some cases, it is not possible to achieve a near-zero source impedance.

A typical moving coil microphone has an impedance of 200 ohms, and some equipment which has passive attenuation or equalization after the final stage may have an output impedance of several kilohms — ideal circumstances for the in-

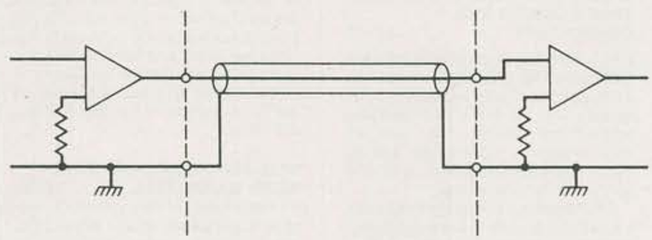

Fig. 1 An unbalanced signal connection, as used on most domestic audio equipment.

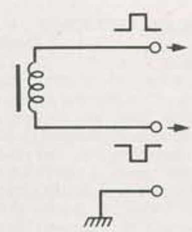

Fig. 2 A balanced output as provided by a moving coil microphone or a transformer.

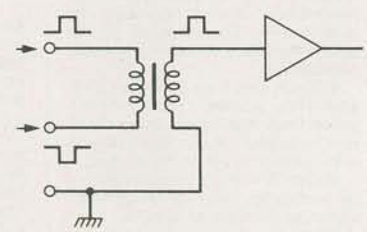

Fig. 3 A differential (or balanced) input using a transformer.

troduction of noise whenever connected to a few metres of cable.

Yet microphones in particular are often required to be at the far end of several hundred meters of conductor, along which a signal with a level of 1mV or less must travel with as little corruption as possible. Can any thing be done to minimize the pick-up of hum, noise and RF that doesn't require considerable lengths of metal conduit piping? Luckily, it can, and it's called balancing.

The easiest way to understand how balanced connections work is to consider a moving coil microphone. It will consist of a thin foil diaphragm to which is attached a lightweight coil, suspended in a powerful magnetic field. The diaphragm and the coil are vibrated by incoming sound waves, and this vibration is turned into an electrical current by the action of the magnet. The ends of the coil are connected to the microphone output socket (Fig. 2) where the output signal voltage appears with a phase difference of 180 degrees between the two contacts.

Let's turn to a type of input circuit usually referred to as differential and typified by the transformer arrangement shown in Fig. 3. In order to produce an output voltage, the transformer inputs must receive two signals which are identical in every way except that they must exhibit a 180 degree phase difference — just what the microphone gives out.

If the two outputs of the microphone are now connected to the two transformer inputs, a balanced circuit is created. In practice, the two conductors are enclosed by a screen layer which in the example given would connect the metal case of the microphone to the input amplifier ground. This is shown in Fig. 4 along with the amplification stage which follows the input transformer.

You may wonder what is so different between that and an unbalanced connection. Luckily, there is a big difference. If the cable connecting a balanced output to a balanced input picks up any hum and noise, the unwanted voltages will occur in both conductors at the same level and most importantly, with the same phase. Since a balanced circuit requires a 180 degree phase difference between its two inputs, any signals arriving which are not in anti-phase are cancelled by the differential action of the input. This removes the hum and noise.

The ability of a balanced input to reject unwanted signals is called the Common Mode Rejection Ratio (CMRR for short), and is measured as shown in Fig. 5. CMRR values tend to be frequency conscious, rejection becoming progressively worse with increasing frequency. By careful design, particularly with solid state inputs, a rejection of 80 or 90dB across the audio band may be achieved.

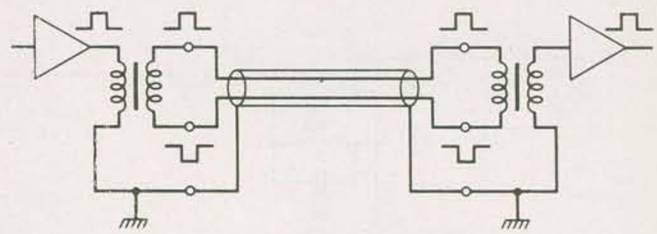

Fig. 4 A balanced interconnection between two pieces of equipment.

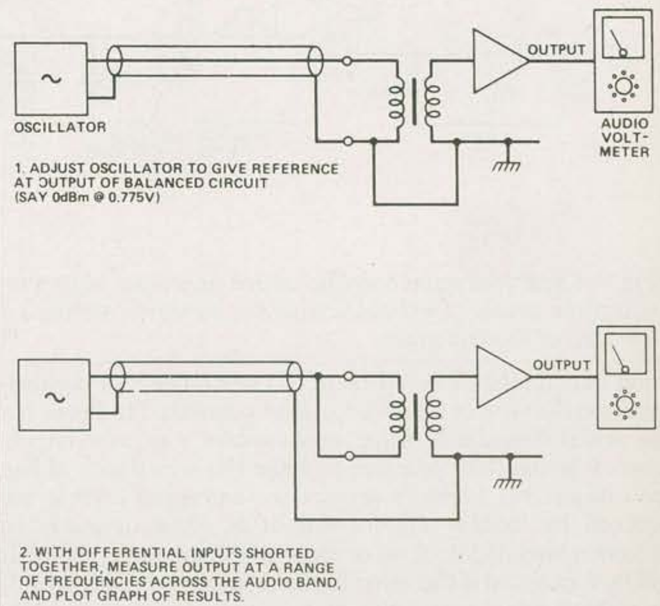

Fig. 5 Measuring the Common Mode Rejection Ratio (CMRR) of a differential input.

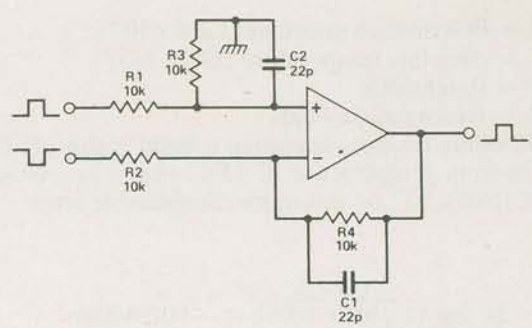

Fig. 6 Balanced input circuit using a single op-amp.

Transformer Or Solid State?

Until recent years, the standard balanced circuit invariably employed transformers for both input and output coupling. By using transformers the signal can be madè to pass from the output of one piece of equipment to the input of another without an ground reference, so removing the risk of hum loops. This is particularly important in radio and TV studios, so transformer balancing is almost universal in these environments.

Transformers do suffer from a number of shortcomings. Without becoming too large for comfort, they will only pass a limited signal level before introducing large amounts of very nasty distortion, particularly at low frequencies. They can also suffer from undesirable phase shifts unless carefully designed. High quality transformers are also rather expensive — 'Professional Grade' versions can cost as much as \$50-\$100.

Although balancing (and unbalancing) transformers are still used in large quantities, for many applications they are being rapidly replaced with solid state input and output stages. A standard operational amplifier has a differential input, and can be connected to a balanced line, as shown in Fig. 6. To obtain the best common mode rejection, the four resistors must all be of the same value, and it is usual to use a variable and fixed resistor in series for R3 to allow the CMRR to be trimmed at low frequencies. The two capacitors also need to have the same value, and C2 is often small trimmer in parallel with a fixed component that is lower in value than C1. With careful adjustment, the CMRR can be as high in value as 90dB across the audio band. This circuit can give excellent results, but has a few shortcomings which rule out its use in high quality equipment.

The two inputs have differing impedances because R2 is terminated by a virtual ground whereas R1 is loaded by R3 in parallel with the input impedance of the op-amp. Unequal

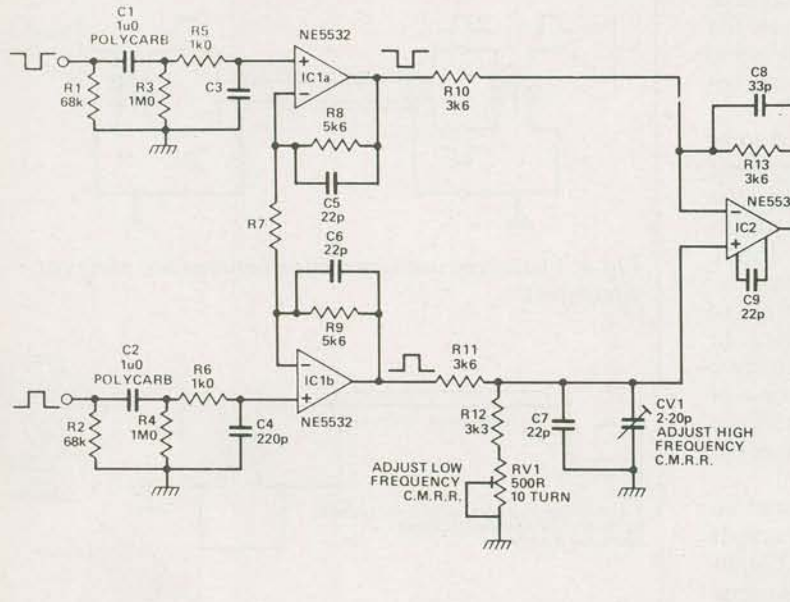

Fig. 7 A balanced input amplifier which uses input buffers to reduce the values of resistance required, thereby achieving a low level of thermal noise.

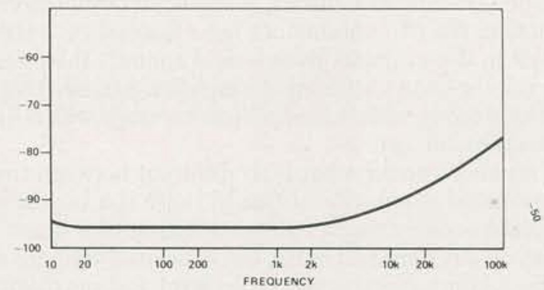

Fig. 8 The common mode rejection offered by the circuit of Fig. 7.

input impedances may not be of too much concern depending upon the type of balanced output connected to them, but the actual impedance value may assume a greater importance. It is standard practice to make the impedance of line level inputs 10k ohms or greater so that signal level is not reduced by loading effects, and it is often desirable to present a load of 50k ohms or more to the incoming signal. It will be found that if the value of the resistors is increased sufficiently to give a reasonably high input impedance, say 33k, then thermal noise has to be considered.

The noise voltage of a resistor is given by:

$$\sqrt{4kTBR}$$

Where k = Boltzmann's constant (1.381×10^{-6})
T = Absolute temperature (C° + 273)
B = Bandwidth
R = Resistance in ohms

For a 33k ohms resistor, assuming a band width of 20kHz and an ambient temperature of 25°C, the noise voltage is therefore 3.296×10^{-6} or, in a more recognizable form:

$$20 \log \left(\frac{0.775}{3.296 \times 10^{-6}}\right) = -107.4\text{dBm}$$

which is not particularly brilliant. Now, if the resistor value is reduced by a factor of 10, its noise contribution will be reduced by 10dB, which is a significant improvement.

A practical circuit which takes account of thermal noise problem is shown in Fig. 7. It is essentially the same as the circuit shown in Fig. 6 except that buffers have been added to each of the inputs. These allow the impedance of each input to be the same and of virtually any value required, yet the resistances around the differential stage may be low enough to avoid noise problems. An additional advantage is that the stage gain can be adjusted by changing one resistor – R7. The gain is calculated from:

$$20 \log \left(\left(\frac{R8 + R9}{R7}\right) + 1\right)$$

or for a required gain,

$$R7 = \frac{R8 + R9}{A \log\left(\frac{Av(dB)}{20}\right) - 1}$$

This stage is ideal for the line level inputs operating over a gain range from unity to 20 or 30dB. It has low noise, negligible distortion (typically 0.002% over the audio band) and excellent common mode rejection (see Fig. 8). To adjust RV1 and CV1, use the set-up shown in Fig. 5. With a 100Hz input signal, set RV1 so that the circuit output voltage is at its minimum level, then reset the oscillator to 15kHz and trim CV1 for minimum output.

This circuit is often referred to as an 'Instrumentation' input. As well as being an ideal balanced input stage for pre and power amplifiers, mixing consoles etc, it also makes a suitable input for many types of high quality test equipment. Audio frequency voltmeters, distortion meters and many other instruments use the circuit because it has very stable and clearly defined gain characteristics and a wide bandwidth with an extremely flat frequency response. With the component values shown in Fig. 7, the -3dB points are at approximately 0.5Hz and 150kHz with less than 2° of phase lead at 20Hz and about 7° of lag at 20kHz.

A number of changes may be introduced to optimize the circuit for specific applications. Input noise may be reduced by replacing C1 and C2 with 10u or 22u non-polarized electrolytics (not forgetting to put a 100n polycarbonate in parallel with each one in the interest of sound quality!) This will also give a few more dB of common mode rejection at low frequencies, and the phase shift at 20Hz will be reduced to 0.06. For use in test equipment, C3 and C4 should be reduced to 47p in order to keep the response flat to 100kHz.

Stage gain may be made adjustable by using a single pole switch to select different values of R7 or a potentiometer in series with a fixed resistor (see Fig. 9). Note that AC coupling has been introduced to avoid problems from switch clicks or potentiometer wiper noise which would otherwise arise due to inevitable DC offsets at the op-amp inputs.

If an accurate stepped attenuator is placed in front of this circuit and some additional gain stages added after it, you have the input stage of a professional-quality audio voltmeter which will give FSD readings from 300V to 10uV – a range of 150dB! (When some further development work has been carried out, you may have the pleasure of constructional article based on it).

So far, we have looked at the balancing of high level signals, but there are far more benefits to be gained by employing the same techniques when signal levels are in the milli or microvolt region. For a high quality microphone amplifier, the basic configuration of Fig. 7 may be used but with a few important changes.

The biggest single problem with microphone amplifiers is keeping the noise contributed by the active stage as low as possible. The thermal noise of a 200 ohm source is 129.6dBm, so a perfectly silent microphone amplifier with a gain of 60dB and a 200 ohm input load, would have an output voltage of -69.6dBm over a 20kHz bandwidth. If a real amplifier has an output of -67dBm, it is said to have a noise figure of 2.6dB. Some manufacturers claim noise figures as low as 1dB, but 1.5dB is a more realistic aim, and the circuit of Fig. 10 can achieve this providing great care is taken with construction and component choice.

The input impedance is fixed at 1k2 ohms by R4, this being the currently accepted value for loading 200 ohm

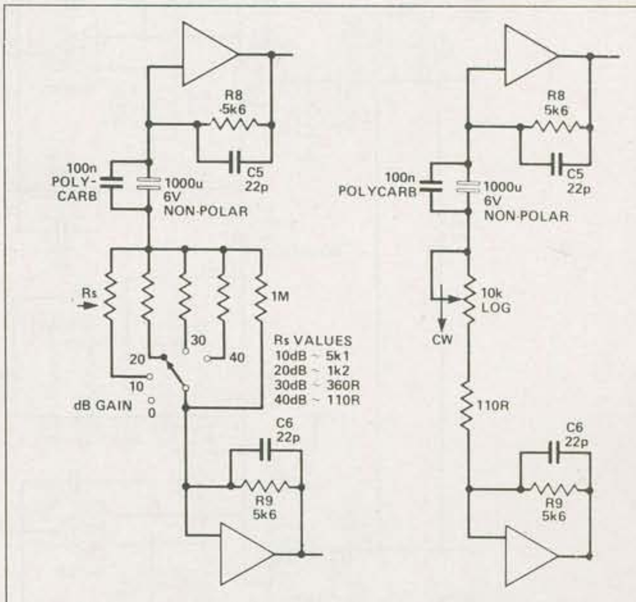

Fig. 9 The circuit of Fig. 7 can be modified to provide either (a) switched gain or (b) continuously variable gain.

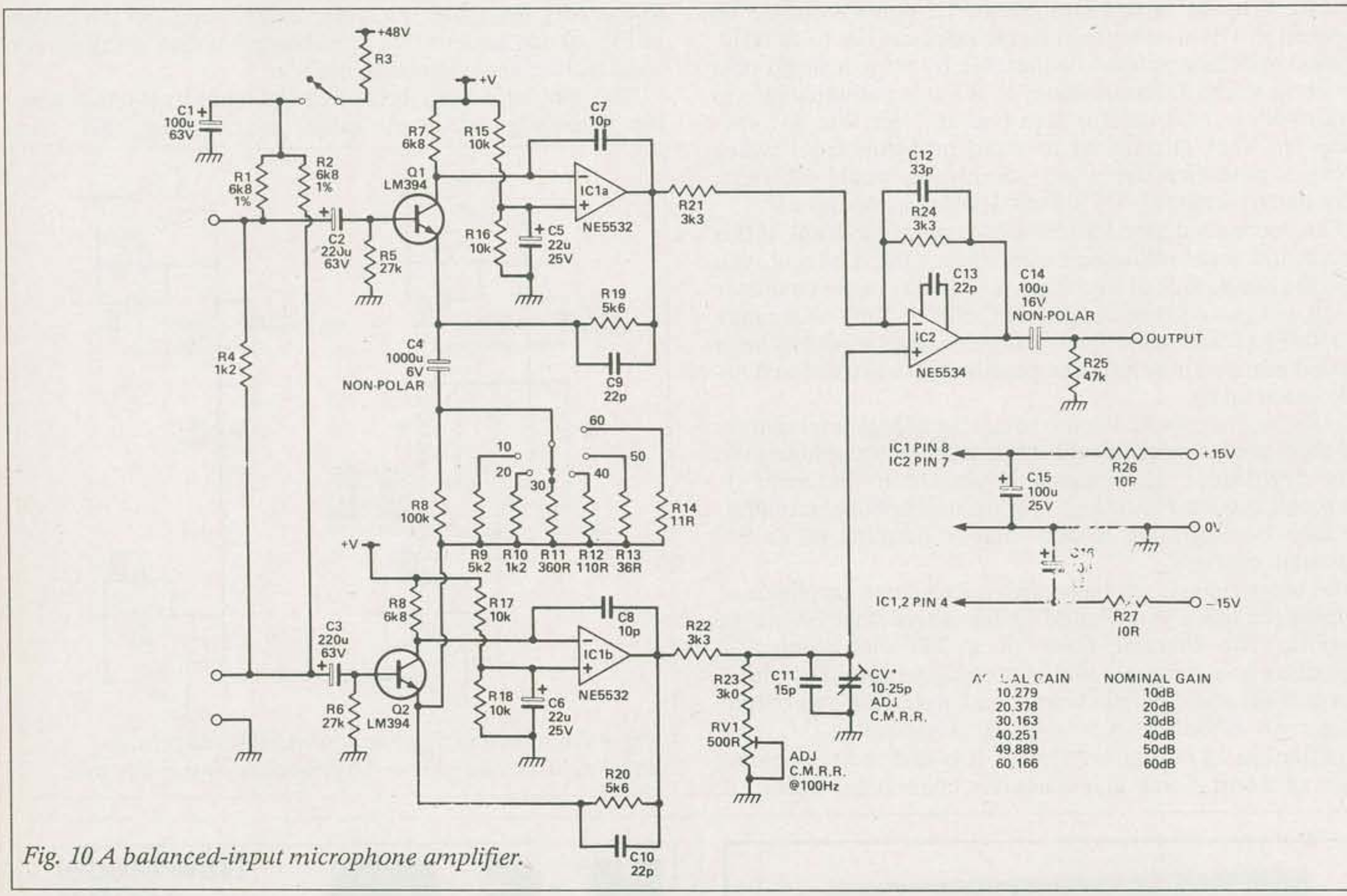

Fig. 10 A balanced-input microphone amplifier.

microphones. It may be changed if a different value is recommended by the microphone manufacturer. R1 and R2 apply 48V phantom power to energize capacitor microphones and should be closely matched, either by purchasing 1% tolerance components or by measuring with an accurate bridge of a digital multimeter. If the circuit is only to be used with dynamic microphones, R1, R2 and R3 together with C1 may be omitted, as may C2 and C3. This will give a slight improvement in signal-to-noise ratio and an improvement in sound quality due to the loss of a pair of electrolytic capacitors from the signal path. As the common mode rejection is adjusted at a part of the circuit that comes after the gain setting stage, there will be a variation of rejection with gain. Although more impressive rejection can be obtained at 10dB gain than at 60dB it is preferable to carry out the adjustment at the 30dB or 40dB setting.

With a carefully designed PCB layout, this circuit will perform as well as and possibly better than any professional microphone amplifier currently available.

Balanced Disc Stage

Another type of input stage that benefits from balancing is the RIAA pick-up amplifier, particularly when a low output moving coil cartridge is in use. Fig. 11 shows the disc input of a particular unit, which has a balanced input. Using such an arrangement may mean that minor surgery has to be carried out on the wiring of your pick-up arm in order to remove the ground connections from the signal leads, but the results will be found to justify this annoyance. Try it and see.

Balanced Mixing

The final balanced input circuit I have shown is that of a virtual ground mixing amplifier. Mixing busses are extremely sensitive to hum and noise, but the problem can be greatly reduced by adopting a balanced mixing system. Two basic arrangements are possible, the input channel amplifiers having either single-ended outputs or balanced outputs (Fig. 12). In both cases the signals feed into a differential input, and any noise voltages picked up along the bus lines will appear at the mixing amplifier inputs with the same phase and will be cancelled in the usual way.

A practical circuit for a differential input mixing amplifier is shown in Fig. 13. It resembles the line input circuit of Fig. 7, except that here the incoming signals are taken to the inverting inputs of the op-amps. The use of 3k3 resistors for feedback and mixing helps keep the noise down and the linearity is improved by having the input capacitors inside the feedback loop. With 3k3 input resistors, this circuit will accept up to fifty inputs with no low frequency problems and will attenuate common mode noise from mixing busses ten or twelve feet long by 60-80db

Balanced Outputs

Microphones and pick-up cartridges are intrinsically balanced, but amplifier outputs are not. The easy way out is to hang a transformer onto the end of a single-ended output stage, but in this day and age it is rumored that miraculous things can be done with a handful of chips and a bit of ingenuity.

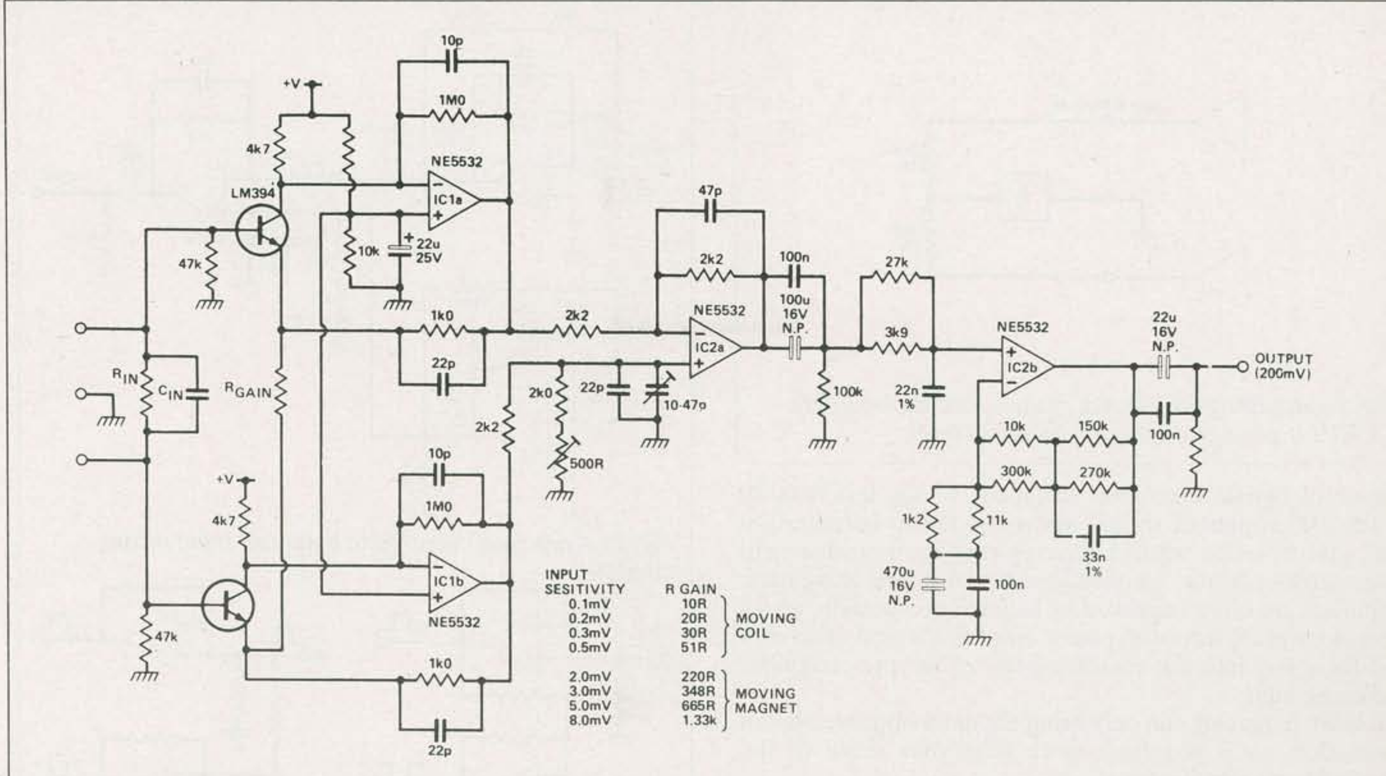

Fig. 11 A balanced-input disc stage, providing RIAA equalization and suitable for use with moving coil cartridges.

If a balanced output is just two outputs in phase opposition, there are several ways of obtaining this (see Fig. 14). They all have on failing – namely that if one output is shorted to ground, the output level drops by 6dB because the peak-to-peak voltage swing is halved.

A solution is shown in Fig. 15, a balanced output stage which delivers the same level into balanced and unbalanced inputs. When this is used with an unbalanced input, it is essential that the unused output is shorted to ground as distortion and noise will otherwise increase.

The operation of this circuit is fairly obvious. Disregarding the input buffer, assume a 1V input at A which feeds both the inverting and non-inverting op-amps. Taking the inverting stage first (IC2a), you may expect there to be -1V at point B. Instead the cross-coupled feedback through R10 is attenuated by the potential divider R10, R7 and puts +0.25V onto the non-inverting input of IC2a. This is then amplified by 2 (think of R5 as a feedback shunt resistor connected to 0V) so the output becomes $-1+(0.25\text{x}2) = -0.5\text{V}$. The non-inverting amplifier (IC2b) has a gain of 2 due to R8 and R12. Its input is held midway between the input voltage and the voltage at B due to the dividing action of R6 and R11. The output of IC2b is therefore

$$2\left(\frac{-0.5+1}{2}\right) = +0.5\text{V}$$

The output between B and C is consequently 1V.

In the unbalanced mode with output C grounded, the feedback voltage via R10 no longer exists, so IC2a with its gain of 1 gives an output of -1V at B. If B is shorted to ground, the voltage at the non-inverting input of IC2b becomes +0.5 which is amplified to 1V and appears at C. Unfortunately,

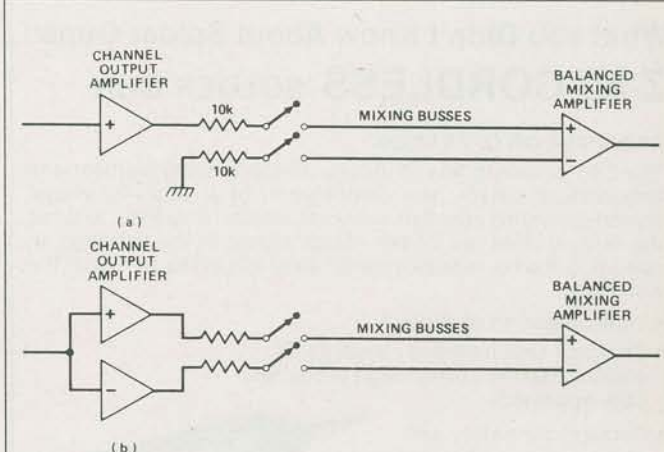

Fig. 12 Balanced mixer arrangements using (a) single-ended amplifiers and (b) balanced-output channel amplifiers.

this balance is not so easy to achieve in practice, primarily due to component tolerances. To overcome this, a preset (RV1) is used to load one output more than the other until the balance is exact. This should be set so that both outputs are exactly the same level when measured with respect to ground. An easy way to make this adjustment is shown in Fig. 16.

So, now you know how to balance. The question remains, do you know what to balance? Any interconnection between two pieces of audio equipment can be balanced by the addition of a few op-amps, but it is rarely worth interfering with low impedance unbalanced connections which are carrying

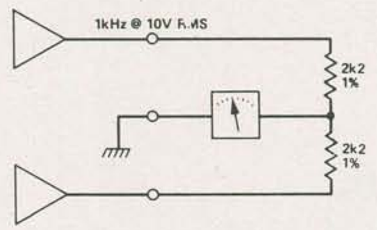

Fig. 16. Adjusting the balance of the circuit shown in Fig. 15. RV1 is set to give a minimum output level.

high level signals over short distances – say less than 20 meters. Microphones should always be fed to balanced inputs, and it is also worth balancing pick-up cartridges and tape recorder heads. Connections between pre and power amplifiers are often improved by balancing, especially where ground currents from the power amplifier would otherwise find their way into the sensitive parts of the pre- amplifier and cause hum.

In brief, balancing can only bring about an improvement in a situation, so if you have more than your share of the dreaded hums give it a try.

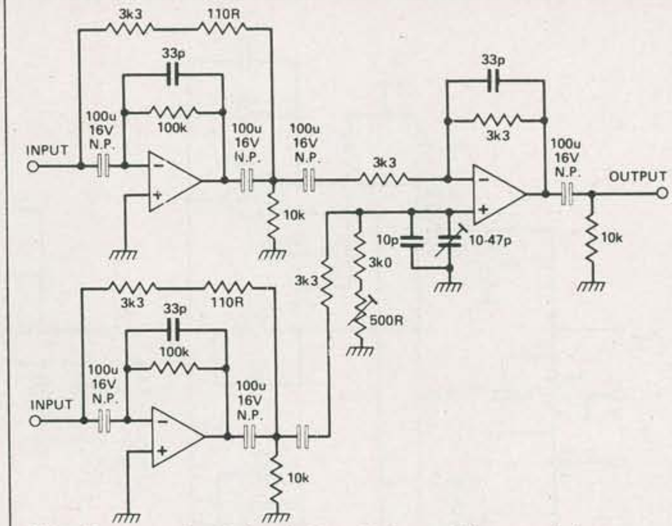

Fig. 13 A practical circuit for a balanced-input mixing amplifier.

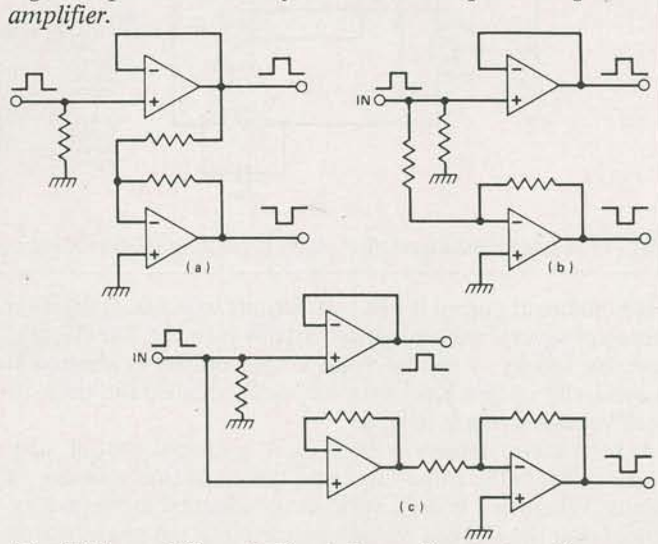

Fig. 14 Some differential (or balanced) output configurations.

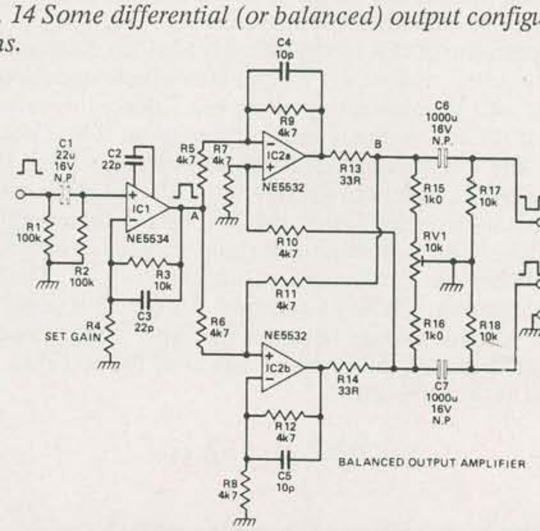

Fig. 15 A balanced output amplifier. The cross-coupled feedback increases the output of either op-amp by 6dBm when the opposite output is shorted to ground, thus allowing the circuit to drive unbalanced inputs as well as balanced ones. ■