Audio Pre-amplifier using Operational Amplifier Techniques

by Daniel Meyer

It has been obvious for some time that the level of performance that can be obtained from the common two- or three-transistor pre-amplifier circuit is no longer adequate in systems of the highest quality. In a typical circuit of the type shown in Fig. 1, the open-loop gain will be a maximum of 60 or possibly 70dB. If the closed-loop gain is set at a reasonable value, say 30dB, the distortion is rather high at the lower frequencies where equalization requirements make considerable bass boost necessary. At 30Hz over 18dB of boost is required and as a result the circuit has only 10 to 15dB of negative feedback remaining. This can quite easily result in distortion in the range of 1% or more, which cannot be tolerated any longer with better grade systems.

The solution is a pre-amplifier circuit with better linearity, or more feedback; which requires a higher open-loop gain to begin with. There are many ways to approach this design problem, but one of the most interesting and rewarding seems to be to approach the circuit as a special operational amplifier. This has been done in the Motorola MC1303 integrated circuit with generally good results. Performance is more than good enough in most respects, but its noise and allowable output loading are not up to the best standards. Both characteristics are due to problems inherent in integrated-circuit fabrication. Noise tends to increase as the number of processing steps increase and it is no problem at all to find individual transistors that will give better noise figures than those on the chip.

Integrated-circuit designers seem to consider the amplifier's performance as a d.c. amplifier more important than its characteristics that would be of interest in audio-frequency circuits. Characteristics such as input bias current, input offset current and voltage, while important in a d.c. amplifier, are of little importance in an audio amplifier. In an audio system we are interested primarily in the following characteristics

- distortion generated by the circuit when used as an equalized pre-amplifier
- noise generated by the input amplifier
- dynamic range, or maximum input level
- input and output impedances.

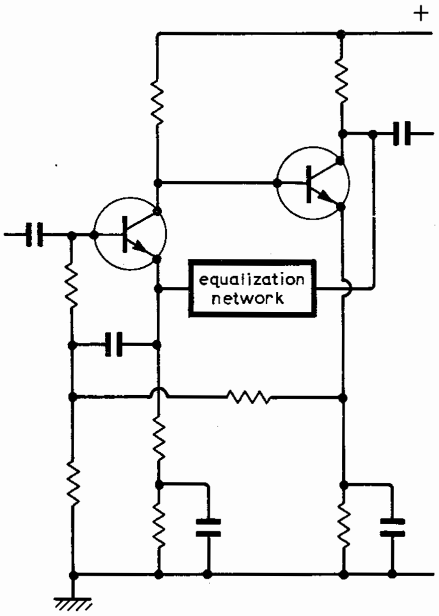

Fig. 1. With conventional pre-amplifiers of the type shown, equalization results in relatively high distortion at low frequencies — R.I.A.A. correction of 18dB boost at 30Hz means there is relatively little negative feedback at l.f.

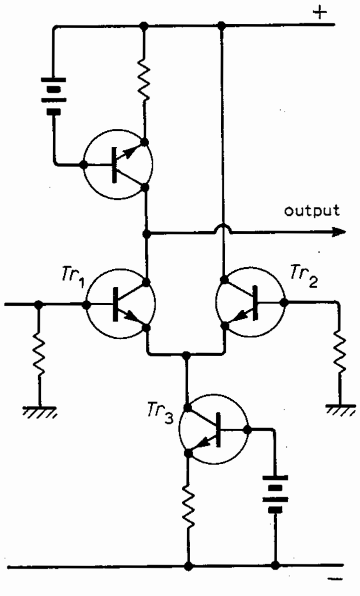

Fig. 2. Better linearity means more feedback means more open-loop gain. Use of a 'dynamic' current source as a collector load increases gain.

As the intended use is as an audio-frequency amplifier, input matching becomes unimportant. The amplifier will have unity gain at d.c. under closed-loop conditions and any small offset that may exist in the output due to mismatch in the input voltage and/or currents will be unimportant. We also do not have to be concerned with compensation that will produce a stable amplifier with gains all the way down to unity. The circuit can be designed with the knowledge that midband gain will be around 30 to 40dB.

Designing the circuit as a special-purpose operational amplifier gives us two useful characteristics. First we find that all signal input and outputs are at d.c. earth potential. This is very handy in designing a complete system because it is no longer necessary to worry about the effects of coupling capacitors charging and discharging when switches are thrown, or potentiometer wiper positions are changed. Second we have a circuit whose gain is set by the values of two resistors in the feedback loop, so performance is consistent despite variations in component characteristics.

Design details

The input stage, in common with almost all operational amplifiers, is a differential amplifier whose emitters are fed from a current source. The current source is normally included to increase common-mode rejection, but in this case it is only used to increase the circuit's isolation from the negative supply rail. The input signal in Fig. 2 sees the collector circuit of the current-source transistor Tr_3 as a high-impedance path back to the negative supply. As a result rejection of ripple or voltage fluctuations is improved considerably. Transistors Tr_1 and Tr_2 split the current from the current source between them. The standing current is chosen to give an optimum noise figure for the transistor being used, in this case 100μA.

To obtain the lowest possible distortion from the stage it must have as high a gain as possible. As has been pointed out by J. L. Linsley Hood[*] and others, the inherent non-linearity of the bipolar transistor is reduced as gain is increased. Maximum gain is obtained by using a

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[*] "The Liniac", *Wireless World*, Sept. 1971 vol. 77 pp. 437-41.

dynamic load in the collector circuit. Such a load has substantially higher dynamic impedance than its d.c. resistance. A dynamic load may consist of a bootstrapped load resistor, an "active" load, or a current source. The current source is the least troublesome and is used in Fig. 3. The current-source stage Tr_3 is biased by the two 1N914 diodes and the current that it will pass is controlled by the value of the emitter resistor. Provided that the base bias voltage is stable the dynamic resistance will be proportional to the reciprocal of the slope of the collector current-base current characteristic of the transistor. The flatter the slope, the higher the impedance.

A fixed resistor is added in series with the current-source transistor's collector to isolate the collector-base capacitance from the signal path at high frequencies. Due to the very high dynamic impedance presented by the current-source and the collector of the amplifier, a relatively small amount of capacitance can cause a pole in the amplifier response within the audio range. To prevent loading of the input stage collector circuit and loss of gain, an emitter follower is used as a matching device between stages. The emitter follower (Tr_4 in Fig. 3) drives the base circuit of the second amplifier stage Tr_5. A current-source collector load is again used for maximum gain and best possible linearity.

Output impedance of this circuit is quite high in its open-loop state, but again unlike a general-purpose operational amplifier, this is not important. The circuit will always be used in a closed-loop system and as the feedback is taken from this point, the apparent impedance will be reduced by a factor proportional to the amount of feedback. In this particular case the open-loop gain will be around 110dB and the output impedance around 100kΩ. As the desired closed-loop gain will be 30 to 40dB, the output impedance will be reduced to a few hundred ohms. The open-loop gain of Tr_1 is about 68dB and that of Tr_5, 45dB.

Maximum output voltage depends on the supply voltage used and the loading that is applied to the output of the circuit. With a +15 and −15V supply and a 10-kΩ load at the output, a maximum of 7V r.m.s. can be obtained before overloading or clipping occurs. In a circuit of this type the load impedance across which you can produce full output is a direct function of the value of the emitter resistors of Tr_5 and current source Tr_6, which control the standing current of this stage. This is interesting because it can be used as the basis for an unusual type of class A power amplifier. Fig. 4 shows the maximum output that can be obtained with various values of loading using the specified supply voltages. Supply voltages can be increased to as much as +25 and −25V with the transistors specified. Maximum input level will be a direct function of supply voltage given a constant closed-loop gain, so as high a supply voltage as possible should be used if this is an important specification in the system.

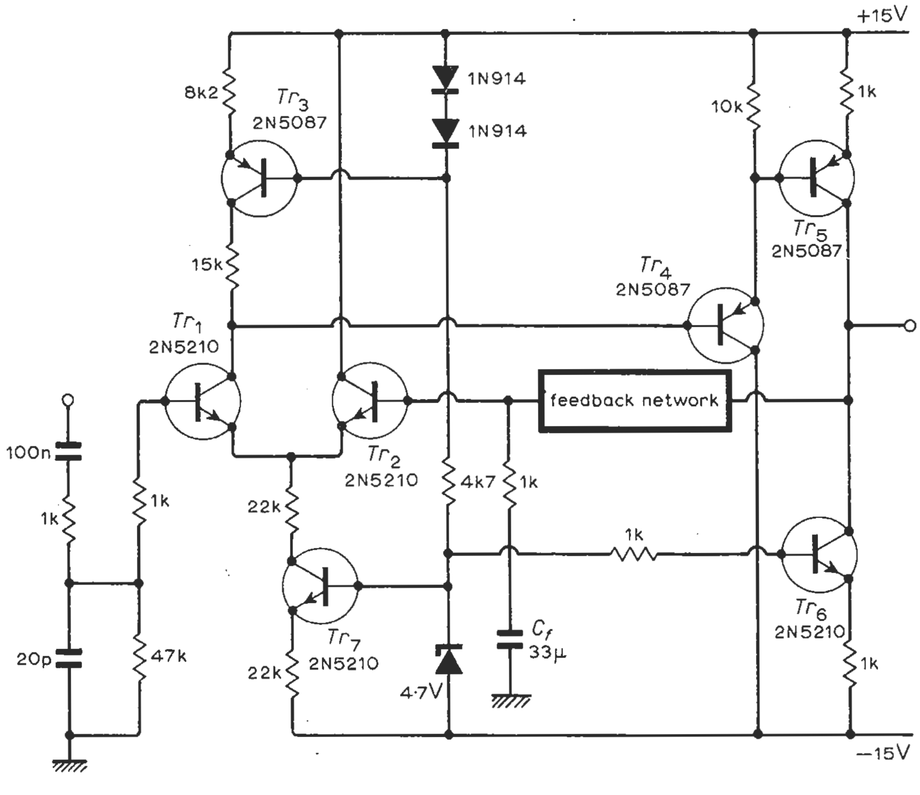


Fig. 3. A current source load, Tr_6, is also used for the second amplifier transistor Tr_5. Tr_1 provides 68dB of gain and Tr_5 45dB.

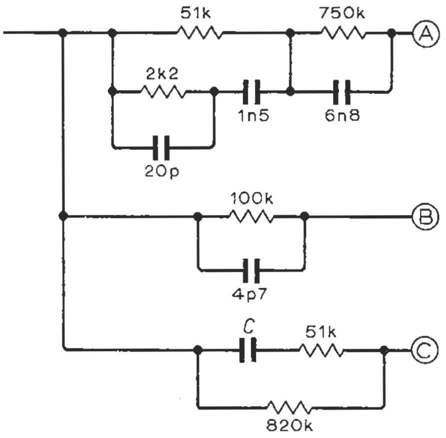


Fig. 6. Equalizing networks for Fig. 3 circuit. Values are for magnetic disc pickup A, dynamic microphone B, and tape head C. Capacitor C should be 910pF for $7\frac{1}{2}$in/sec and 1.5nF for $3\frac{3}{4}$in/sec. Component tolerances should be 5% or better.

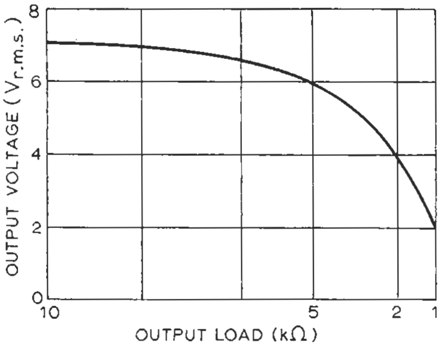


Fig. 4. Load impedance across which full output can be produced is a function of Tr_5 and Tr_6 emitter resistors which control standing current (assumes 15-V supplies).

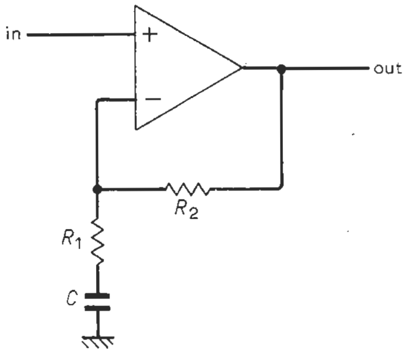
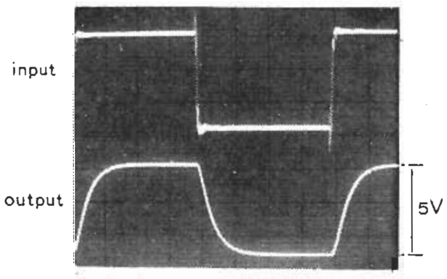


Fig. 5. Overall gain is $(R_1 + R_2)/R_1$. Resistor R_1 is 1kΩ and R_2 is in the feedback network — Fig. 6.



110-kHz square-wave response of circuit using network B of Fig. 6. Sweep: 1μs/cm.

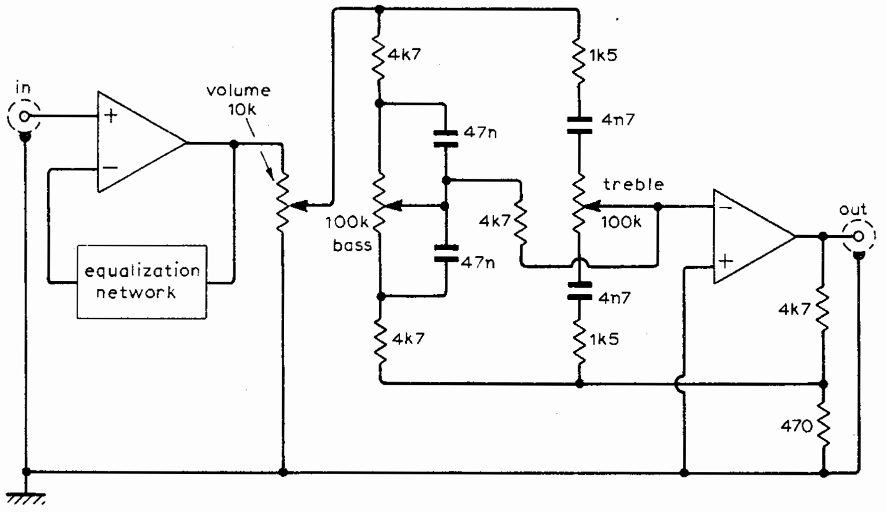


Fig. 7. Suggested circuit for pre-amplifier with Baxandall-type tone controls. Distortion at maximum lift is better than 0.01% at normal levels.

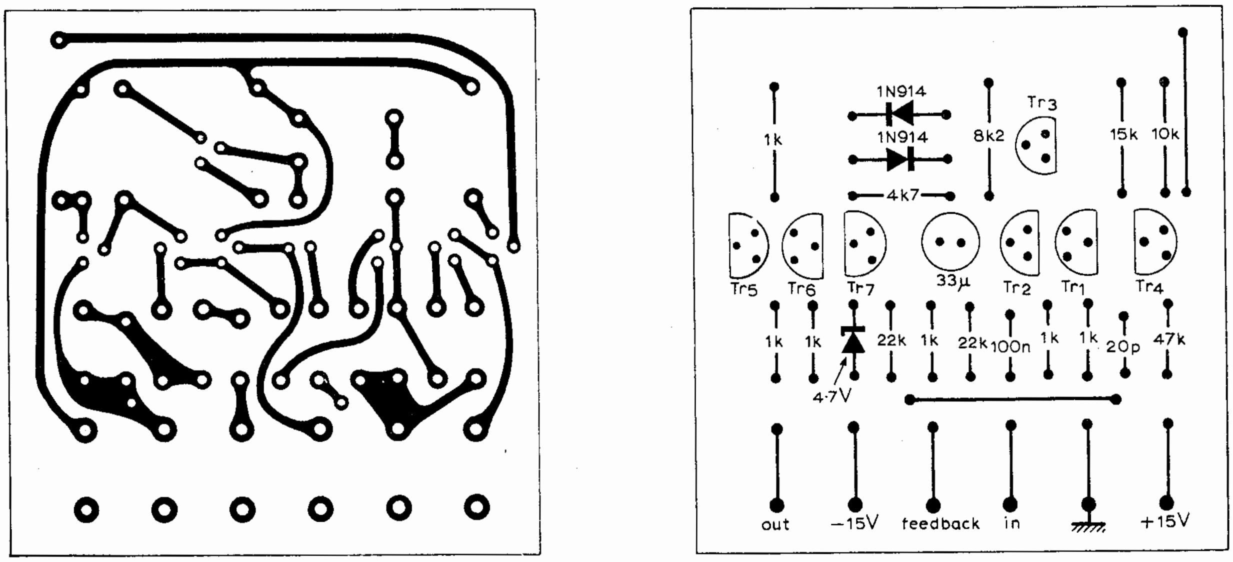


Fig. 8. Suitable printed board layout. Feedback components can be mounted on switch contacts. Components are shown mounted on the side opposite to the conductors.

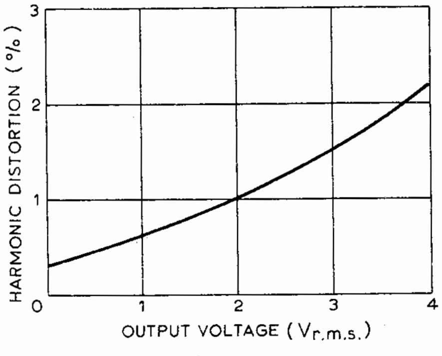
Feedback networks

When a signal is applied to the non-inverting input of an operational amplifier as shown in Fig. 5, the gain is $(R_1+R_2)/R_1$. The capacitor in series with R_1 reduces the gain to unity at d.c. Due to the large amount of feedback used, the input impedance of the circuit is well over 1MΩ and a resistor must be added in parallel with the input of the circuit to properly load a magnetic cartridge, the most common value of 47kΩ being shown. The small capacitor in parallel with this resistor rolls off the response at frequencies over 200kHz, ensuring that the generator impedance as seen by the circuit cannot become infinite at high frequencies.

Networks needed for R.I.A.A., microphone (flat), and tape head equalization are shown in Fig. 6. The 2.2-kΩ resistor and 20pF capacitor in the magnetic (disc) network shape the response past 50kHz. This is not normally necessary in a lower-gain, or narrow-bandwidth circuit, but is essential here if optimum transient response at higher frequencies is to be obtained. The photo shows the response of the circuit to a 100-kHz square-wave input using the flat microphone network. Rise time will be reduced if a high-impedance signal source is used, but in no case will it be greater than 2.5μs.

Complete circuit

Fig. 7 shows a pre-amplifier channel with tone controls using the circuit. The circuit is an excellent driver for a Baxandall-type tone control system, the arrangement shown giving approximately 20dB of gain, and bass and treble lift and cut of approximately 20dB at 30Hz and 20kHz with respect to 1kHz. Maximum-lift distortion of this circuit, which is the worst case condition, is better than 0.01% at normal output levels — considerably better than the widely used single-transistor driver circuit under the same maximum lift conditions.



Output voltage vs harmonic distortion before feedback is applied.

Performance

harmonic distortion	<0.01% at 1-V output, 20Hz to 20kHz
hum and noise	>80dB below 10mV input
maximum 'undistorted' output	7V r.m.s. with 15-V supplies and 10kΩ load
maximum input	100mV with 'magnetic' network
input impedance	<1MΩ at 40-dB gain
output impedance	>1kΩ at 40-dB gain
open-loop gain	110dB
supply voltage	+10 to +25 and −10 to −25V
drain	10mA at 15V

The number and types of inputs is left to the builder. High-level inputs may be switched directly into the volume control, or reduced in level by a suitable resistive divider and applied to the pre-amplifier input. This seems to do little harm with a circuit of this quality and makes switching far simpler. In this way only two switch decks are required, one to

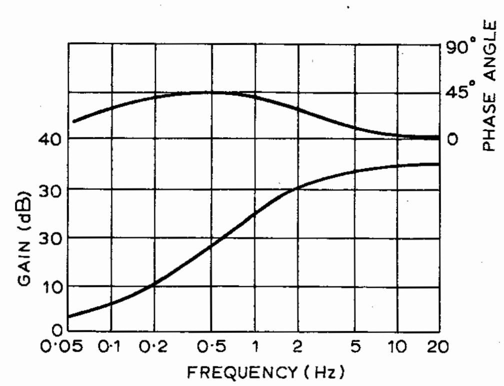


Fig. 9. Effect of l.f. roll-off capacitor C_f

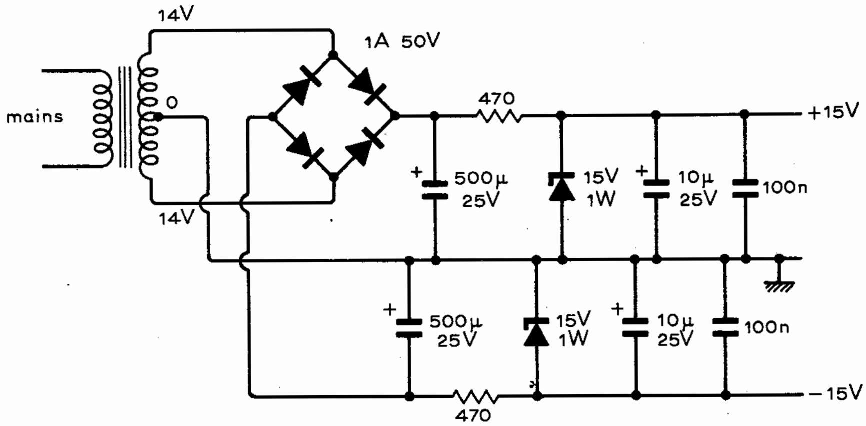


Fig. 10. With this power supply, hum is 80dB below 10mV input.

switch the inputs and one to switch the equalization networks.

The circuit was designed as a plug-in unit on a small printed-circuit card. The circuit board pattern and parts locations are shown in Fig. 8. This type of construction makes screening of the circuit in a metal enclosure simple and also makes it easy to encapsulate the completed circuit in resin if desired. Leads carrying low-level signals should be shielded if more than an inch or two long and grounding loops should be avoided. Resistors and capacitors in the equalization network can usually be mounted directly on the selector switch lugs. Components should be 5% or better tolerance in this portion of the circuit. The capacitor at the input was added to ensure that no direct voltage could be applied to the input transistors from an external source. If such is not likely in your application the capacitor should be removed. The low-frequency roll-off point is determined by the value of capacitor C_f in the base circuit of Tr_2. As can be seen from Fig. 9, the gain falls off below 5Hz and approaches unity below 0.1Hz. Phase shift reaches a maximum of approximately 55° between 0.5 and 1.0Hz and then decreases again as the input frequency approaches zero.

A suitable power supply for the pre-amplifier is shown in Fig. 10. With this supply the pre-amp will have hum and noise typically better than 80dB below 10mV input. A complete pre-amplifier and control system using the gain modules as described will have a total harmonic distortion of less than 0.01% at any frequency and under any conditions below its overload point. The extremely wide bandwidth and freedom from ringing or overload on transients makes the pre-amplifier very pleasant to listen to for extended periods. Combined with one of the excellent transistor power amplifiers now available and a first-rate speaker system, it produces a music system second to none. The fact that seven transistors are used makes little difference as they are relatively low-cost plastic package types.