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OPEN LOOP DISTORTION OF OPERATIONAL AMPLIFIERS AND ITS IMPLICATIONS FOR HIGH QUALITY AUDIO SYSTEM DESIGN

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INTRODUCTION

The operational amplifier (op-amp) has become an ubiquitous component in audio systems. The ease with which it can be applied in audio circuitry has resulted in its use whenever a general gain block is required. However, the operational amplifier was originally developed to implement the operations on analogue computers. In this application low frequency characteristics such as input offsets and DC gain are important because they directly affect the accuracy of the computation. Designers of op-amps have followed this philosophy by providing us with op-amps which have voltage offsets measured in microvolts and DC gains measured in millions. Unfortunately, because of the need to ensure unity gain stability the gain of these amplifiers has to be unity at a frequency between 3 and 10MHz with a 6dB per octave rolloff. This means that at 10kHz the typical open loop voltage gains of these amplifiers is 50 to 60dB (316-1000) irrespective of their DC gain. In fact the open loop gain at audio frequencies of op-amps is more a function of their unity gain bandwidth than their DC gain. Therefore for audio applications the open loop characteristics of an op-amp will have a significant effect on the closed loop performance. Especially at the higher audio frequencies where the desirable reduction of distortion and output impedance by the feedback factor will be less. For example, an amplifier with an open loop distortion of 11% operating at a closed loop gain of 100 would have a distortion of 1% at 10kHz.

The rest of the paper first discusses, with reference to typical op-amp topologies, sources of open loop distortion. Circuits which appear to have unity gain but in fact have an implied gain are then discussed and finally recommendations for circuit design are given.

SOURCES OF DISTORTION

Figures 1 and 2 [1,2] show the typical topologies of current op amps, bipolar and bifet respectively. They both have a differential input stage, a class AB unity gain buffer stage and a common emitter amplifier prior to the output stage. They both also use a current mirror to perform the differential to simple ended conversion of the input signal. However the bifet uses a simple emitter follower between the input stage and the common emitter amplifier whereas the bipolar amplifier has an additional longtailed pair driven by emitter followers which buffer it from the first stage. Both amplifiers have dominant pole compensation but the bipolar op amp has some additional feed-forward compensation to improve its gain bandwidth. The common emitter stage typically has a gain of ≈ 1000 and this stage must provide an output voltage swing of ≈ 30Vpp. Therefore its input voltage will be typically 30mV at low frequencies. This stage is likely to contribute a large amount of 2nd harmonic distortion due to a variety of effects.

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If this stage is voltage driven (as in the bifet amp) then one can show [3] that the 2nd harmonic distortion of such a stage is given by:

$$D_{2nd\ Harmonic} = \frac{1}{4}\left[\frac{q}{KT}\right]^{Vin} \quad (1)$$

where Vin is the peak input voltage.

The third harmonic is given by:

$$D_{3rd\ Harmonic} = \frac{1}{24}\left[\left[\frac{q}{KT}\right] Vin\right]^{2} \quad (2)$$

If one substitutes the typical input voltage swing of 30mV pp and a typical value of $\frac{1}{26mV}$ for $\left[\frac{q}{KT}\right]$ we get distortion levels of 14% 2nd harmonic and 1.4% third harmonic (worst case). If the stage is current driven (as in the bipolar stage) the distortion level should be less because it is then dependent on the variation of β with I_C. However the presence of a collector to base capacitance whose value is a function of the collector to base voltage results in distortion which rises with frequency.

Paradoxically the dominant pole compensation helps reduce the high frequency distortion of this stage by providing local negative feedback. Howewver this means that the voltage swing at the current mirror must be higher. This results in an increase in the distortion contributed by that stage especially as it is operating at a V_{ce} of around 600mV. The other major source of distortion is the class AB output stage. This contributes distortion in several ways. Firstly crossover distortion which will be inherent in any class AB stage (although this can be reduced by choosing the standing current of the output stage carefully). Secondly the variation of the output transistors β with current results in a collector load of the common emitter which depends on current output thus causing distortion. Thirdly it is possible for the power dissipation variation of the output transistors to be fed back to the input stages of the device via thermal feedback [4]. This can cause a rise in distortion at low frequencies.

Another source of distortion is common mode distortion. This is again frequency dependent because it depends on the common mode rejection of the amplifier. This type of distortion results in an increase in distortion when the amplifier is used in a non inverting configuration because of the signal dependent common mode signal which results. Distortion may also be caused by signal dependent modulation of the power supply voltages; however, these can be reduced by appropriate power supply design.

CIRCUIT IMPLICATIONS

Clearly then one must avoid high values of closed loop gain if one is to preserve distortion performance at high frequencies. It would seem that a closed loop gain of 30dB (31.6) would be about the most one would want to have as this would still allow 30dB of negative feedback at 10kHz. While this seems a fairly simple rule to follow there are many circuits which, although they have a low gain, have an implied gain which is much higher (e.g. some types of active filter). Two examples illustrate this. The first one is the popular virtual earth mixer as shown in figure 3. In this arrangement the end to end gain is 1 but the N-1 other source form a resistor to ground of value $^{R}/_{(N-1)}$ thus causing the input signal to be attenuated by a factor of N. As the feedback is also attenuated by the same factor the overall gain is 1 but the amplifier has had to amplify the signal by the factor N to achieve this. For a 32 input mix this is an implied gain of 30.1dB. A second example is the swinging inputs equaliser shown in figure 4 again with the control set at centre (Flat) we have unity gain overall. However the input signal is attenuated by a factor of ≈ 3 at the centre frequency of the resonance. Therefore the amplifier must make up this loss. The effect is worse when you have multiple sections on the same input as the amplifier must then make up even more loss. As it also has to have the capability of providing the necessary boost gain one can run into problems.

A DESIGN EXAMPLE

Figure 5 shows a state variable active filter two of the amplifiers have frequency dependent feedback. Whereas one has purely resistive feedback. The two integrators have a closed loop gain with the same slope as the open loop gain and hence the feedback factor is the same at all frequencies. Thus it is possible to ensure that these amplifiers have sufficient feedback to reduce the distortion to low levels. The summing amplifier however does not have this advantage and therefore can have an insufficient feed back factor especially if a high Q filter is required. So it is this amplifier that one should ensure has adequate high frequency gain or low open loop distortion.

CONCLUSIONS AND RECOMMENDATIONS

Open loop distortion is an issue when considering applying operational amplifiers to audio circuit design. Critical parameters for device selection should be the open loop gain and distortion at 10-20kHz. A secondary parameter might be the effect of thermal feedback. Circuit design must be carried out with the idea of a falling open loop gain characteristic as a function of frequency to ensure that adequate feedback is maintained. In particular any circuit with a low overall gain which contains components (either reactive or resistive) that are connected between the input and an AC ground should be carefully analysed to see if the "hidden" make up gain required is within the amplifier's capability.

Should one require more gain at 10kHz than is provided by standard compensation then one can consider either two pole, feedforward or input pole-zero compensation (figs 6, 7 and 8 respectively) as a way of increasing the 10kHz gain. Alternatively if the circuit is not going to operate at unity gain use an undercompensated version.

Finally the op amp is not a universal panacea; use it sparingly in the knowledge that inside it contains the same non-linear components which caused problems when discrete circuitry was the norm.

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REFERENCES

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[2] *The BIFET design manual*, 2nd ed, Pub Texas Instruments Ltd, p8.

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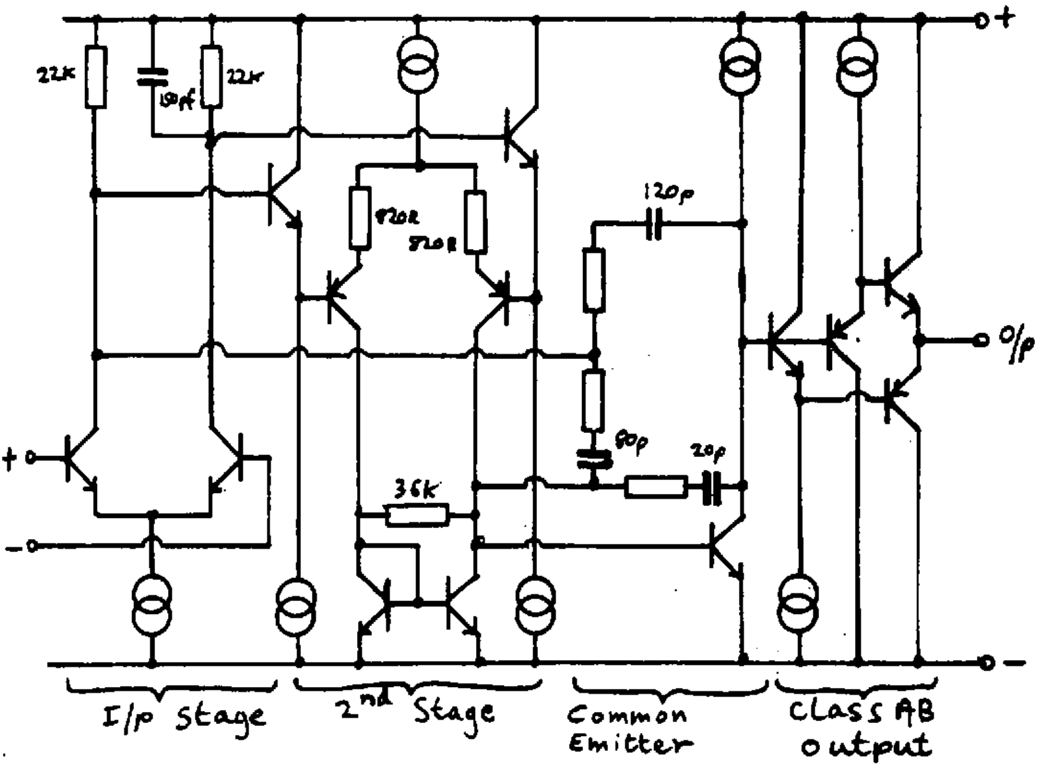

Figure 1 Bipolar op-amp topology

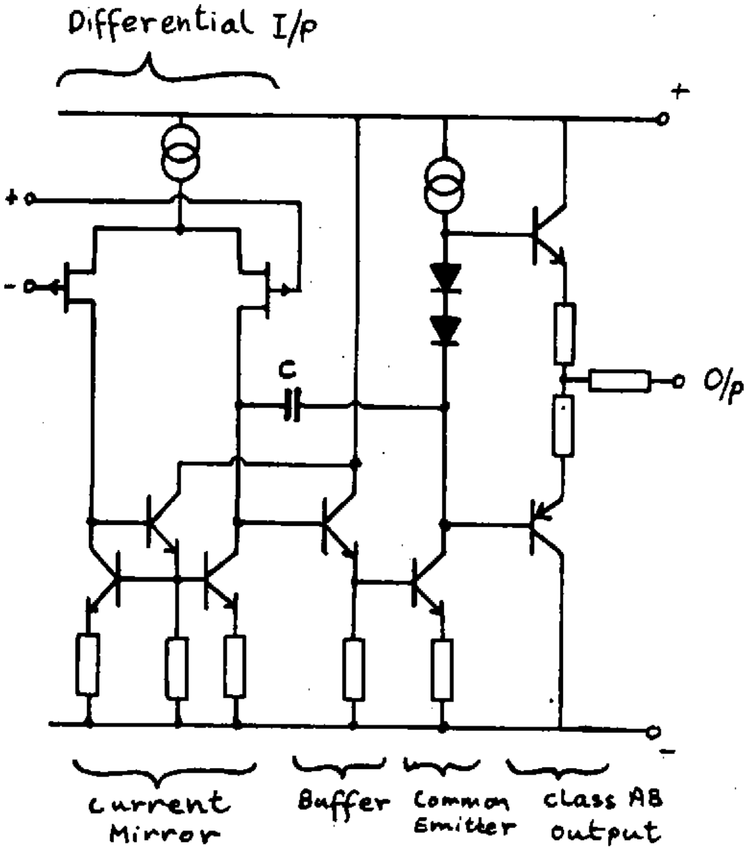

Figure 2 Bifet op-amp topology

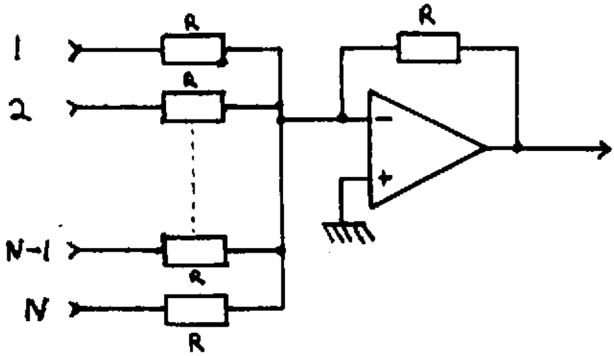

Figure 3 Virtual earth mixer

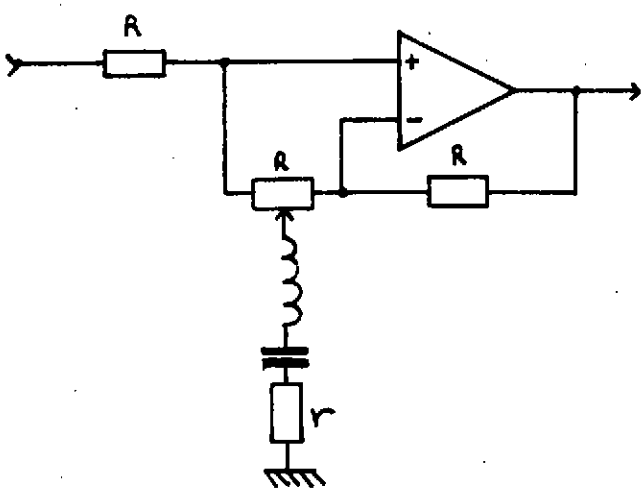

Figure 4 Swinging input equaliser

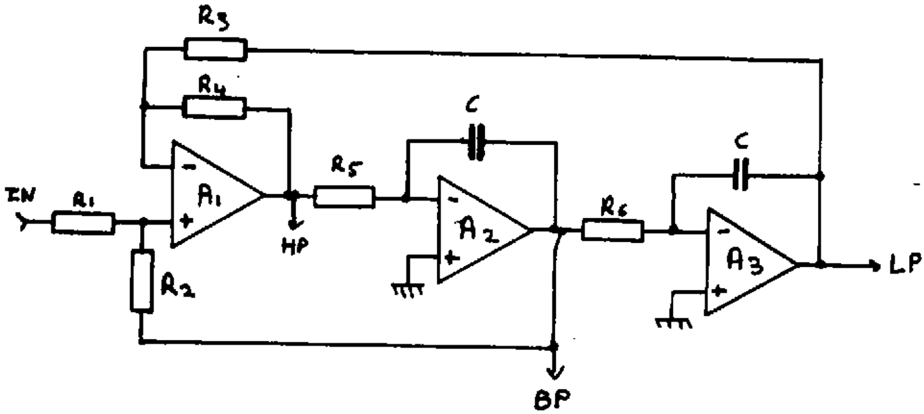

Figure 5 State variable filter

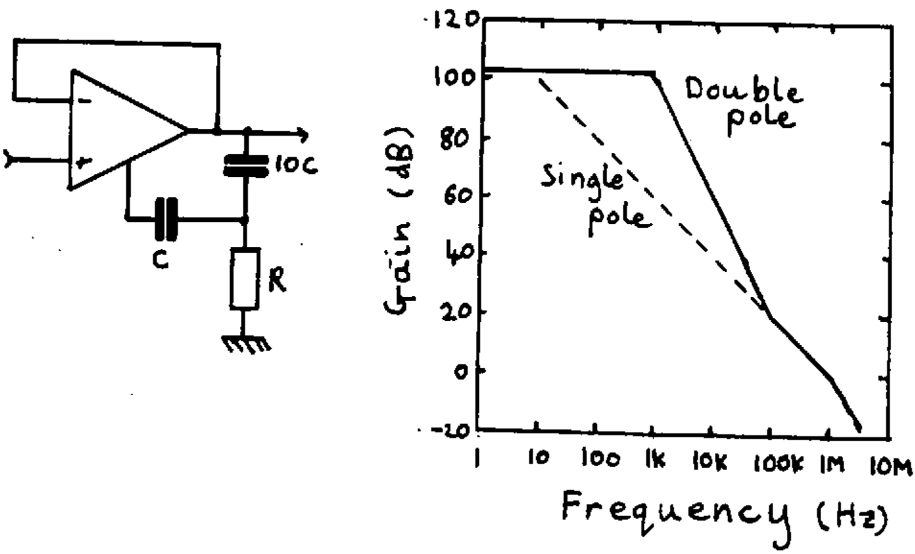

Figure 6 Double pole compensation

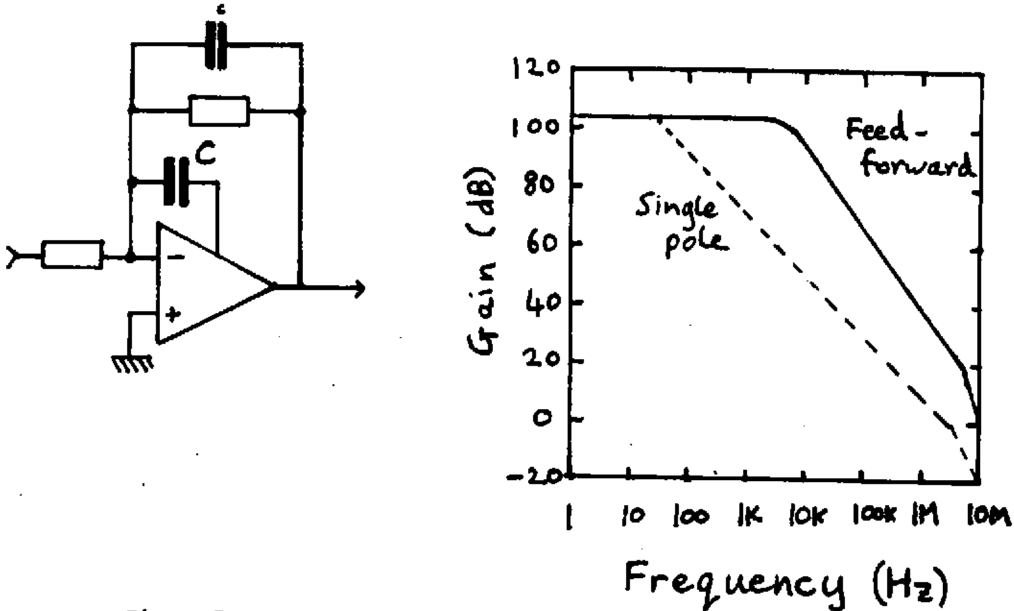

Figure 7 Feedforward compensation

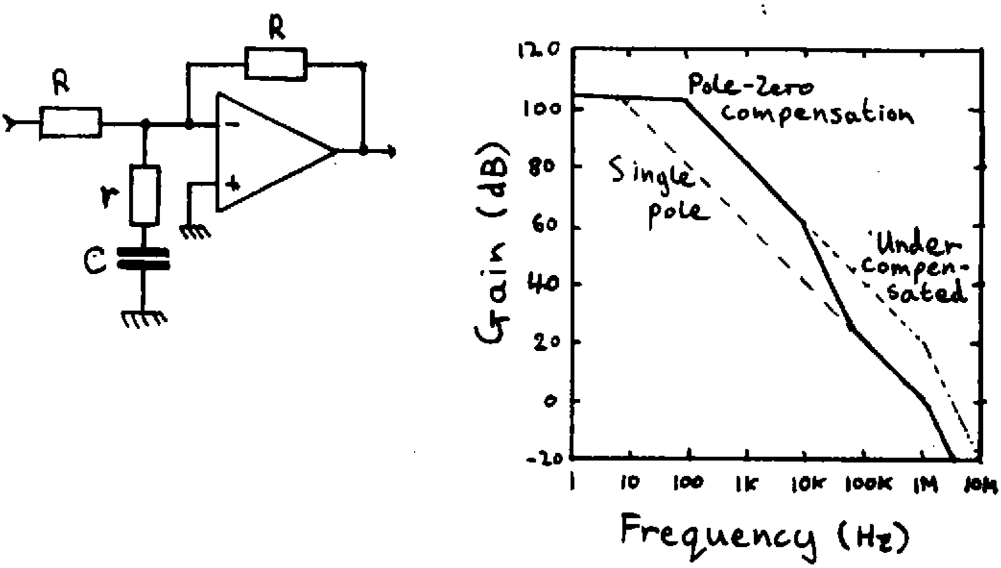

Figure 8 Pole-zero compensation