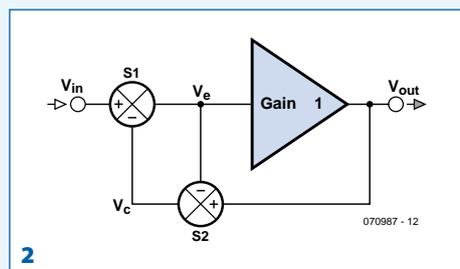
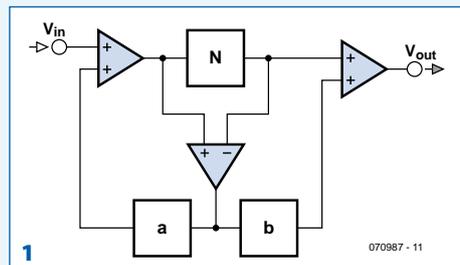


PaX amplifier stability

Dear Jan — I would like to comment on the article on the paX Amplifier by Jan Didden in the April 2008 issue of *Elektor*.



Error correction

Around 80 years ago already, before feedback was commonly used, Black obtained a patent on feedforward error correction. Due to the limited availability of suitable components at that time, this principle was not used on a large scale until much later. The

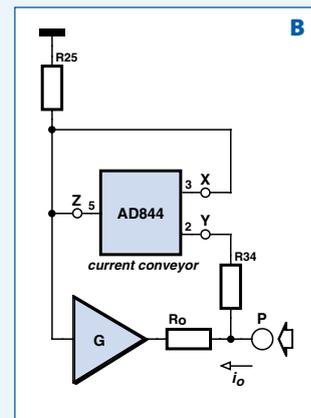
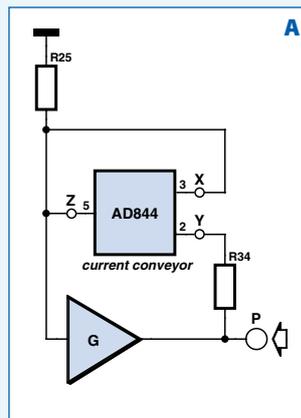
basic scheme of Hawksford [1], as shown in **Figure 1** of Didden's article, is often used as the starting point. If $a = 0$ and $b = 1$, feedforward error correction is present. If $a = 1$ and $b = 0$, there is feedback error correction. Accurate addition of the correction signal at the output is difficult with a power amplifier, which is why the feedback approach is often used. In **Figure 2** of the article, S1 and S2 are idealised functions whose purpose is to add the error correction signal to V_{in} at the input. However, the problem here is that a replica of the error signal must be generated. As a result, conversion stages are necessary to transform current into voltage and voltage into current. This means that the accuracy of the replication process is dependent on the matching of pairs of transistors and/or resistors. As a result, the replication factor K can be less than or greater than 1. This inaccuracy influences distortion reduction, and possibly other characteristics of the circuit as well. It is thus desirable to analyse the stability of the amplifier as a function of K .

Feedback error correction

The basic circuit shown in Figure 2 of Didden's article is based on a form of feedback. My version of a simple equivalent circuit of the feedback loop is shown in **Figure A**.

As far as I know, this is the first time that the use of a current conveyor for this purpose has been described in a published article. If Z is connected to X , the current conveyor acts as a current mirror with 100% voltage feedback. In order to analyse the feedback loop, the input terminal is connected to ground. The behaviour of the current conveyor is idealised in order to avoid complex formulae: $V_x = V_y$, $A_i = 1$ (where A_i is the current gain of the current mirrors in the current conveyor). The error signal V_e , which in this case is the signal between the Z and P terminals, is converted to a current by $R34$. As a result

of the current mirroring action of the current conveyor, a current with the same value flows in $R25$ if $A_i = 1$. This current produces a replica of the error signal across $R25$ if $R25 = R34$. Now it is extremely important for the loop gain H_{loop} to be less than 1. If H_{loop} is equal to or greater than 1, latch-up will occur with a DC-coupled circuit such as the one shown in the figure.



This means that depending on the polarity of the DC offset, the output level will gradually increase until it reaches the positive or negative supply voltage. With the previously mentioned simplifications, the loop gain H_{loop} is given by:

$$H_{loop} = (1 - G) \times R25/R34 = (1 - G) \times K \quad [1]$$

Here the replication factor K is equal to $R25/R34$ and G is the combined voltage gain of the buffer and the output stage. This is a special form of feedback, since feedback is present if G is greater than 1, the loop gain is zero if G is 1, and feedforward is present if G is less than 1 (as in the paX amplifier). If G is 0.95 (which is a reasonable estimate of the transfer function of the buffer plus the output stage) and K is 1, the loop gain is 0.05. This is well below the critical limit ($G = 1$). This means that the feedback loop is sufficiently stable with regard to latch-up risk.

Output impedance

The open-loop output impedance of the buffer plus the output stage is shown in **Figure B**. As R_o has a large influence on the non-ideal behaviour of the buffer and output stage, a value of 1 for G can reasonably be assumed for the purpose of calculating the output impedance. The current source i_o (shown here for the sake of the analysis) connected to the output produces a voltage across R_o . A replica of this voltage (just as with the error correction feedback loop) is generated at the Z terminal. This can be expressed by the following formula:

$$Z_{out} = R_o \times (1 - R25/R34) = R_o \times (1 - K) \quad [2]$$

The output impedance Z_{out} is positive if K is less than 1, zero if K is 1, and negative if K is greater than 1. A positive output impedance causes overdamping of the loudspeaker, while a negative

output impedance causes underdamping. As a result, an amplifier with a negative output impedance and a mediocre impulse response will cause overshooting if it is loaded with an LCR network (i.e. a loudspeaker), and in the worst case it can oscillate.

Conclusions and recommendations

From the above, it can be seen that the error correction feedback loop is stable, but the output impedance is negative in the presence of overcompensation. This is undesirable, especially with a problematic speaker load (such as an electrostatic speaker). The output impedance can easily be checked by connecting an audio signal generator to the input of the amplifier. When a load is connected to the amplifier, the amplitude of the output signal will decrease if the output impedance is positive or increase if the output impedance is negative. If the output impedance is found to be negative, the cure is to reduce the value of K by decreasing the value of R25 or increasing the value of R34.

Wim de Jager (The Netherlands)

Response from Jan Didden, the designer of the paX amplifier:

Dear Wim,

Your reasoning with regard to the output impedance is correct. However, if you attach a few values from actual practice to it, it turns out to not be a real problem.

You raise two issues with regard to the stability of the error-correction amplifier implemented in my design.

The error correction resistors (R24 and R25) should be matched as closely as possible for maximum error correction. In practice, 1% matching can be achieved without having to use adjustable resistors or trim pots. This yields an error correction of 40 dB. Furthermore, the loop gain of 0.05 that you mention (with an open-loop output stage gain of 0.95) means that the values of these resistors can differ by up to a factor of 20, or 2000%, with regard to stability considerations. Consequently, latch-up is not an issue.

Your reasoning with regard to the output impedance is also correct. Here again, it is enlightening to consider a few practical figures. A quick simulation shows that the open-loop output impedance of the circuit shown in Figure B is approximately 0.4 ohm (at 10 kHz). If the value of R25 is 1% larger than it should be (relative to R34), this yields a negative output impedance of 4 milliohms. For comparison, the resistance of 1 metre of speaker cable with a 2-mm wire diameter is approximately 10 milliohms.

Here you could say that the negative output impedance offsets the resistance of the first half metre of the speaker cable. If it has any effect at all, it is to improve the damping.

In summary, it appears that a mismatch of the error correction resistors by a few percent does not create any problem at all with regard to latch-up or output impedance. A matching level of 1% can be achieved by a 'clever' choice of standard resistance values.

All of this is confirmed by the trouble-free operation of several dozen amplifiers that have been built according to this design.

Jan Didden

Thanks for that David — will do! By the way, for those keen on statistics: the chunks to compile the ISO file and from there burn your own DVD were down-

loaded 2,880 times and almost bowled over our web servers.