Current dumping analysis

Class B amplifiers without crossover distortion

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The current dumping technique, as presented by P. J. Walker[1], is a very elegant solution to the problem of reducing the crossover distortion in class B audio power amplifiers, because it eliminates the requirement of a quiescent current on the output transistors, and the thermal problems associated with biasing. However, the amount of controversy[2-8] that followed Mr Walker's article denotes that the current dumping principle has not received a complete treatment. The purpose of this work is to show, by means of a more complete analysis, that current dumping does reduce the crossover distortion more than conventional feedback but it is not able to totally cancel this distortion on the output stage, even with a "theoretically perfect balance" or infinite feedback factor.

In Fig. 1, the general arrangement of the current dumping technique, the class A amplifier has a finite gain A, and it is shown later that the balance condition does not require A to be infinite. This configuration is general in the sense that all the current dumping circuits are possible realizations of it. The flow-graph of this configuration is presented in Fig. 2, and helps to understand how both feedback and feedforward are employed.

The two basic equations for the amplifier in Fig. 1 are

$$V_1 = A(V_s - kV_2), \qquad 1$$

$$\frac{V_o}{R_L} = \frac{V_1 - V_o}{R_3} + \frac{V_2 - V_o}{R_4} \Rightarrow$$

$$\frac{V_o}{R_p} = \frac{V_1}{R_3} + \frac{V_2}{R_4} \qquad 2$$

where $R_p = R_L // R_3 // R_4$. These equations cannot be solved for V_o/V_s unless a third equation is introduced, if no particular values for R_3 and R_4 are assumed. The action of the dumper gives this equation. Its transference from V_1 to V_2 can be written as

$$V_2 = BV_1$$

where B can be a highly non-linear factor, in which are present crossover effects. With this relation equations 1 and 2 become

$$V_1 = A(V_s - kBV_1) \Rightarrow V_1 = \frac{A}{1+kAB} \cdot V_s \qquad 3$$

$$\frac{V_o}{R_p} = \frac{V_1}{R_3} + \frac{BV_1}{R_4} \Rightarrow V_o = \frac{R_p}{R_3}\left[1 + \frac{R_3}{R_4} \cdot B\right] V_1 \qquad 4$$

which, combined, finally lead to

$$\frac{V_o}{V_s} = \frac{R_p}{R_3} \cdot \frac{A}{1+kAB} \cdot \left[1 + \frac{R_3}{R_4} \cdot B\right] \qquad 5$$

which is the desired relation between input and output. The heart of current dumping is to make the denominator of the second factor equal to the third factor, which is attained if

$$\frac{R_3}{R_4} = kA \qquad 6$$

Making this substitution in equation 5 the term $1+kAB$ is cancelled, and

$$\frac{V_o}{V_s} = \frac{R_p}{R_3} \cdot A \qquad 7$$

This result is the reason for all the excitement that has involved the people that worked on current dumping, because it states that the output signal does not depend on the dumper transfer characteristic! This is highly impressive, because a look to Fig. 1 reveals that if $R_3 \ll R_4$ the dumper will be the main source of power to the load when it is on (i.e. at medium and high signal levels). But as the dumper gain B is not present in equation 7, its crossover distortion will not appear at the output voltage. (Remember that A is the gain of a class A amplifier, and hence free from crossover effects.)

The results of equations 6 and 7 were already known[1,3,5,6,7] in different forms but with the same meaning; that was well defined in an assertion by Mr Walker[4]: ". . . there is a theoretically accessible state where the output stage distortion will cancel to zero, without calling upon infinite loop gain . . ." Is this really true? Can one get the power of an amplifier (in this case, the dumper) without getting its distortion, too?

In fact, the situation is not so good as it may appear at first sight. A very important point was missed out of the analysis so far, and it was also missed from previous analyses of current dumping[1,3,5,6,7]: the distortion of the class A amplifier. This low-power amplifier must have a very low distortion level, because its distortion will appear at the output, which is clear from equation 7. Because it operates in class A, a very low distortion is not so difficult to achieve, and this problem was left out. However, if the gain A is distorted, even

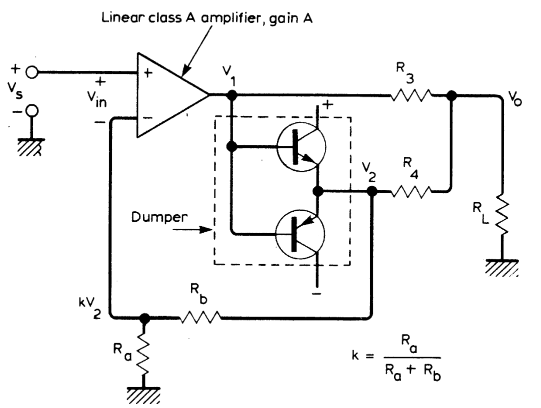

Fig. 1. General arrangement of the current dumping technique. For small signals (V_1<200mV r.m.s.) the output current is supplied by the low-power class A amplifier.

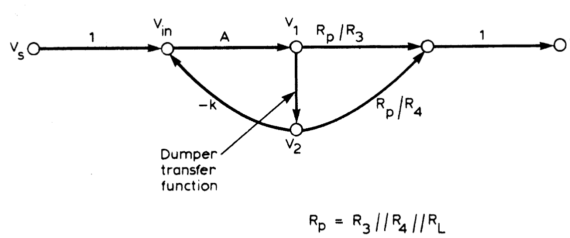

Fig. 2. As the principal power-carrying transmission is that from V_2 to V_o, the transmission from V_1 to V_o is feedforward. Hence it is clear that current dumping uses both feedback and feedforward.

by a small amount, the balance condition of equation 6 will not hold for all signal levels, and the term $1+kAB$ in equation 5 will not be perfectly cancelled.

To clarify the situation, the distortion of both amplifiers must be considered in the analysis. In fact, if one is looking for a distortion reducing scheme, all the distortion sources must be taken into account. A simple way to introduce these distortions is to write the gain of the low-power amplifier as $A(1+D_A)$, and that of the dumper as $B(1+D_B)$, where A and B are fixed constants and D_A and D_B are random variables with unknown distributions that represent the distortion of the class A amplifier and the crossover distortion of the dumper, respectively.

Hence, equation 5 becomes

$$\frac{V_o}{V_s}=\frac{R_p}{R_3}\cdot\frac{A(1+D_A)}{1+kAB(1+D_A)(1+D_B)}\cdot\left[1+\frac{R_3}{R_4}B(1+D_B)\right] \quad 8$$

From this it is clear that there are no finite values for A and R_3/R_4 that can cancel the effects of D_B on V_o/V_s (remember that $R_3/R_4=kA(1+D_A)$ cannot be written, because a random variable cannot be always equal to a constant). An interesting result is obtained if the loop gain is made infinite, i.e. if $A\rightarrow\infty$. It is easy to see, from equation 8, that

$$\lim_{A\rightarrow\infty}\frac{V_o}{V_s}=\frac{R_p}{R_3}\cdot\frac{1}{kB(1+D_B)}\cdot\left[1+\frac{R_3}{R_4}B(1+D_B)\right]$$

$$=\frac{R_p}{kR_4}\left[1+\frac{R_4}{R_3}\frac{1}{B(1+D_B)}\right] \quad 9$$

This shows that even with an infinite loop gain, crossover distortion will be present at the output. It is interesting to note that if the feedforward transmission in Fig. 2 is nulled, i.e. if R_3 is made infinite, thus converting the current dumping into a conventional feedback arrangement, the output will be free from both D_A and D_B. This is the classic result from conventional feedback: infinite loop gain (which is far from being physically realizable due to instability) means zero distortion.

Thus, current dumping is not theoretically able to cancel totally the crossover distortion of a class B power amplifier, either with a finite or infinite loop gain, but it is better than conventional feedback for a finite loop gain and assuming that the balance condition holds. To see that this is true, it is necessary to express the effects of D_A and D_B on V_o/V_s more clearly than in equation 8, which can be written as

$$\frac{V_o}{V_s}=A\cdot\frac{R_p}{R_3}\cdot\left[1+\frac{R_3}{R_4}B(1+D_B)\right]\cdot\frac{1+D_A}{1+kAB(1+D_A)(1+D_B)}$$

As $|D_A|\ll 1$, the last fraction can be expanded in a Taylor series for D_A, around the point $D_A=0$. Using the fact that

$$\frac{\partial^n}{\partial D_A^n}\left[\frac{1+D_A}{1+kAB(1+D_A)(1+D_B)}\right]=$$

$$=\frac{(-1)^{n+1}n!\,[kAB(1+D_B)]^{n+1}}{[1+kAB(1+D_A)(1+D_B)]^{n+1}}$$

the final result is

$$\frac{V_o}{V_s}=A\frac{R_p}{R_3}\left[\frac{1+\frac{R_3}{R_4}B(1+D_B)}{1+kAB(1+D_B)}\right].(1+hD_A-h^2nD_A^2+h^3n^2D_A^3-\ldots) \quad 10$$

$$\text{where } h=\frac{1}{1+kAB(1+D_B)}$$

$$\text{and } n=\frac{kAB(1+D_B)}{1+kAB(1+D_B)}.$$

If the balance condition 6 is satisfied, a simplification can be made in equation 10 (and this is the reason for the minimum in the output distortion already verified experimentally[5,8])

$$\frac{V_o}{V_s}=A\frac{R_p}{R_3}(1+hD_A-h^2nD_A^2+h^3n^2D_A^3-\ldots) \quad 11$$

which shows that current dumping generates high-order distortion, as does conventional feedback.

At this point, it is useful to separate the analysis in two cases, corresponding to the off and on conditions of the dumper.

Dumper off. This condition corresponds to $B(1+D_B)=0$, which implies $h=1$ and $n=0$. Thus equation 11 becomes

$$\frac{V_o}{V_s}=A\frac{R_p}{R_3}(1+D_A). \quad 12$$

So, when the output power transistors are off the transmission from V_1 to V_2 is nulled, which breaks the feedback loop. Therefore, as the output signal is supplied by the class A amplifier only, with no feedback, the distortion factor of V_o/V_s must be D_A, as stated in equation 12.

Dumper on. When the dumper is on, i.e. one of the output transistors conducting, it has little distortion, because it is acting as an emitter-follower, which is implied in $|D_B|<1$. As $kAB\gg 1$ (which follows from the fact that R_3 must be much greater than R_4, the balance condition is $R_3=kAR_4$ and $B\approx 1$), $h\ll 1$ and $n\approx 1$. Hence the series of equation 11 can be truncated to the first power term with little error, and $1+kAB(1+D_B)$ can be replaced by $kAB(1+D_B)$.

These considerations lead to

$$\frac{V_o}{V_s}\approx A\frac{R_p}{R_3}\left[1+\frac{D_A}{kAB(1+D_B)}\right].$$

$$\text{As } \frac{1}{1+D_B}=1-D_B+D_B^2-D_B^3+\ldots\approx 1-D_B$$

for $|D_B|\ll 1$, it follows that

$$\frac{V_o}{V_s}=A\frac{R_p}{R_3}\left[1+\frac{D_A}{kAB}-\frac{D_AD_B}{kAB}\right]. \quad 13$$

So the output has two main distortion components: one due to the distortion of the class A amplifier, which is D_A reduced by kAB (this was expected because D_A is generated within a feedback loop with loop gain kAB), and the other due to the intermodulation of the two distortions, that is

$$D_A\frac{D_B}{kAB}$$

With $|D_A|\ll 1$ the effect of the distortion D_B is reduced by an amount greater than the feedback loop gain kAB. Therefore, the current dumping technique can reduce the effects of the crossover distortion more than conventional feedback, given the same loop gain, even though this reduction cannot be total anyway.

Hence the current dumping allows the design of a power amplifier with output transistors in true class B, avoiding the well-known thermal problems in conventional AB output stages. Further, it is also correct to say that the performance of a current dumping power amplifier is dictated mainly by two factors: the linearity of the low power class A amplifier (see equation 13) and the precision of the balance.

Another important point is the effect of the output impedance of the amplifier A, and the input and output impedances of the dumper, the last two being highly dependent on whether the dumper is on or off. The variation in the output impedance of the dumper can be accommodated by the distortion factor D_B, and then does not affect the results. But its input impedance will affect the term D_A, as the amplifier A cannot have zero output impedance. Therefore the transistors of the dumper must have very high current gains, to minimize the effects of the loading of the linear class A amplifier by a non-linear load. In practice, these transistors must be Darlington pairs or triplets.

From a practical viewpoint, the balance condition is not too difficult to achieve, if the class A amplifier has its gain stabilized by local feedback[1,3,7]. Even if this condition is not satisfied, a balance can be obtained by adjusting k[5] or the resistors R_3 or R_4. As the gain A must have some kind of compensation in frequency due to the feedback loop around it, it seems that the equation 6 will not hold for all frequencies. However, if the compensation is made by a single pole in A, the resistor R_4 can be replaced by a series connection of an inductance and a resistor, in order to create a zero that can cancel the pole[1,8].

Finally, it seems that the current dumping technique is "the state of the art" for reducing to very low levels the crossover distortion (see, for instance, the results of the evaluation of a power amplifier that uses current dumping[8]), thus allowing the construction of high-fidelity amplifiers in true class B.

References

1. P. J. Walker, Current dumping audio amplifiers, *Wireless World*, December 1975, pp. 560-2.
2. Letters to the editor, *Wireless World*, April 1976, pp. 54-5.
3. Letters to the editor, *Wireless World*, July 1976, pp. 60-2.
4. Letters to the editor, *Wireless World*, November 1976, pp. 52-3.
5. Letters to the editor, *Wireless World*, April 1977, p. 76.
6. Letters to the editor, *Wireless World*, June 1977, p. 49.
7. J. Vanderkooy and S. P. Lipshitz, Current dumping – does it really work?, *Wireless World*, June 1978, pp. 38-40.
8. J. Vanderkooy and S. P. Lipshitz, Current dumping – does it really work?, *Wireless World*, July 1978, pp. 83-5.