Current dumping — does it really work?

Theory and practice

by **J. Vanderkooy** and **S. P. Lipshitz** University of Waterloo, Ontario

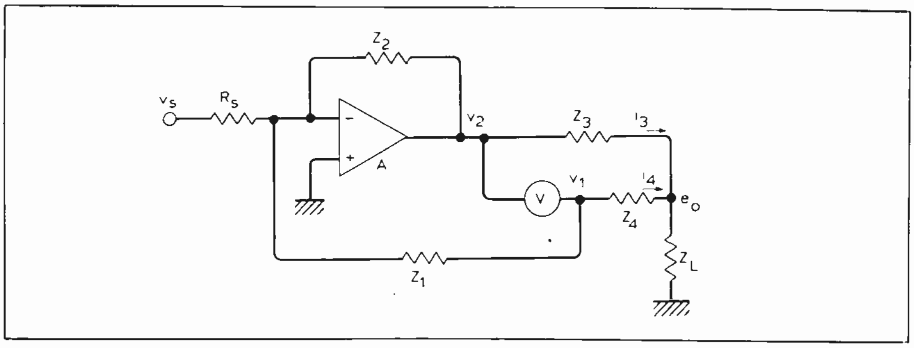
---

This article endorses the soundness of the current dumping principle, though querying whether it should be called feedforward error correction in the feedback loop. In several respects the distortion reduction appears due to a passive bridge balance. It shows that dumper β-variation results in distortion, fortunately very low, which cannot be balanced out in present circuits. Readers are challenged to produce a circuit which nulls out such current distortion as well.

Measurements, in part 2, show that the amplifier performs very well, and analyses of the distortion oscillograms and wave analyser measurements show that, qualitatively, much of this data can be understood. We both heartily agree that the current dumping principle as embodied in the Quad 405 amplifier has significantly advanced the state of the art in class B power amplifier design.

A FLURRY OF EXCITEMENT and controversy has occurred since the article on the current dumping amplifier by P. J. Walker[1]. A class B audio amplifier capable of low crossover distortion, with no quiescent current, seems too good to be true! We have followed the letters to the editor with great interest, and noted that the situation seems to be a stalemate as regards the conventional-feedback versus feedforward argument. Each of us has changed his mind regarding the operation of the amplifier several times. It was in this framework that we decided a more careful analysis was necessary. We present first a view of the theory as we see it, and later on deal with some corroborating measurements made on a Quad 405 amplifier.*

Fig. 1. *Simplified equivalent circuit of the current dumping principle considering only dumper voltage distortion.*



Early letters have been adequately handled by Mr Walker[2], and we feel there is value in the equivalent circuit of Peter Baxandall[3]. But we fail to see how the independence of output impedance under two limiting conditions (dumpers on with infinte mutual conductance, off with zero gain) can imply distortionless behaviour.

There seems to be an advantage in the circuit, but it is precisely in the region of output transistor turn-on that such arguments are inapplicable. Accordingly, we were sceptical of the results, not having really taken the pains to work out all the details presented in Mr Walker's article and the letters. Referring to Fig. (d) of Mr Baxandall's letter, we were led to conclude that the distortion voltage created by the dumpers must somehow find its way out of the otherwise linear components. Mr Olsson's letter[3] also requires an answer.

Simplified analysis

An illuminating but incomplete analysis of the amplifier is possible. The effect of the dumpers can be looked on as a distortion voltage applied between the input and output of the dumper stage. In Fig. 1 assume for now that A has zero output impedance and has infinite gain (both conditions are related later). Labelling v_1, v_2, e_0, v_s, i_3 and i_4 as in Fig. 1

$$\frac{v_1}{Z_1}+\frac{v_2}{Z_2}+\frac{v_s}{R_s}=0,$$

and summing i_3 and i_4 for the total current

$$\frac{v_2-e_0}{Z_3}+\frac{v_1-e_0}{Z_4}=\frac{e_0}{Z_L}.$$

These two equations are easily solved for e_0 in terms of v_s and either one of v_1 or v_2 (we give both for didactic reasons):

$$e_0\left(\frac{1}{Z_L}+\frac{1}{Z_3}+\frac{1}{Z_4}\right)=$$
$$-\frac{Z_2}{Z_3R_s}v_s+v_1\left(\frac{1}{Z_4}-\frac{Z_2}{Z_1Z_3}\right),$$

or

$$e_0\left(\frac{1}{Z_L}+\frac{1}{Z_3}+\frac{1}{Z_4}\right)=$$
$$-\frac{Z_1}{Z_4R_s}v_s+v_2\left(\frac{1}{Z_3}-\frac{Z_1}{Z_2Z_4}\right). \qquad (1)$$

Either equation shows that e_0 will not depend on v_1 or v_2, which have distortion, if $Z_1Z_3=Z_2Z_4$, just the Walker balance condition. Under this condition the output e_0 depends only on v_s (with the same coefficient now) and not on the distortion voltage $v=v_2-v_1$.

If the gain A is made finite, a balance condition will still follow (messy algebra) as long as the amplifier A has zero output impedance, so that the dumper input current can be ignored**. This has been discussed by Bennett and Walker[2].

Another slant on a simplified analysis is to consider the output of the class A amplifier to be a true current source, with infinite output impedance. Then the equivalent circuit can be redrawn as in Fig. 2, with the dumpers again approximated by a voltage source, which admittedly is not very realistic with the current source approximation.

The class A amplifier has been characterised by a transconductance G_m with the output connected to the point v_2. To avoid getting dumper voltage distortion (v) into the output, any signal due to v at the inverting input of the class A amplifier should be zero. This requires $Z_1Z_3=Z_2Z_4$ independent of the value of G_m, because the criterion is simply a passive balance of the bridge. It

---

*As a result of the widespred advertising campagin for the Quad 405, we have heard it referred to as the "currently dumped amplifier." (We trust that the Acoustical Manufacturing Co. will forgive us for this levity.)

**For finite gain A, the dumper distortion v cannot be balanced to zero if the bridge is destroyed by shorting Z_4 in the circuit of Fig. 1. This fact also follows from our more general analysis below.

might be considered passive feedforward error correction in the amplifier with judicious feedback applied.

Naturally the effect of the dumpers is to amplify current, and then such a simple analysis is not warranted. Passive balance is lost and a more general analysis is necessary to establish if a balance condition still exists.

Balance condition

If the balance condition $B=0$ can be achieved (see boxed item) the output e_0 will contain no dumper distortion contributions. The condition $B=0$ is the counterpart of the Walker balance condition $Z_1Z_3=Z_2Z_4$ which followed from setting the coefficient of v_2 equal to zero in our earlier equation (1). This condition is analysed next in some detail as it really contains all the information we have been seeking.

Firstly, returning to a remark made earlier ** suppose that Z_4 is omitted (i.e. short-circuited), thus destroying the bridge. Solving the equation $B=0$ for G_m in this case $G_m =$

$$-\frac{\beta\left\{(Z_1+Z_2+Z_3)R_s+Z_1(Z_2+Z_3)\right\}+Z_1Z_3}{(\beta+1)Z_1Z_3R_s}$$

which is negative†. For d.c. stability, we must assume G_m to be positive so that the overall feedback around the amplifier be *negative* feedback. Thus no bridge balance condition is possible when $Z_4=0$.

Secondly the possibility of achieving bridge balance *does* exist in the general case. Rearranging the equation $B=0$,

$$Z_2Z_4-Z_1Z_3=$$

$$\frac{\beta\left\{(Z_1+Z_2+Z_3+Z_4)R_s+Z_1(Z_2+Z_3)\right\}}{(\beta+1)G_mR_s+1} \qquad \ldots(3)$$

Provided $Z_2Z_4>Z_1Z_3$ and assuming these impedances to be real for the moment, balance can be achieved for finite transconductance G_m *as long as β can be assumed to be constant.* In fact, equation (3) gives the value of G_m re-

---

†Unless explicitly stated otherwise, we assume that Z_1, Z_2, Z_3, Z_4 are real.

More detailed analysis

The Quad 405 contains a class A amplifier which has a current output. Referring to Fig. 4 of Peter Walker's article[1], the collector of Tr_7 is the output of this amplifier. The resistor R_{30} is not a significant load as it is "bootstrapped away" by C_{10}. Other connections to this point are the dumper bases, Z_2 and Z_3. Capacitors C_9 and C_{11}, presumably to prevent r.f. instability, are ignored. Hence in an improved modelling circuit we consider the class A amplifier to have a current output and a traconductance G_m from input (emitter of Tr_2) to output (collector of Tr_7). Capacitor C_8 (Z_2) does not really connect to the same point as $R_{20\text{-}21}$ (Z_1), something about which more will be said later. Consider now the circuit shown in Fig. 3, ignoring Z_0 for the moment.

Dumper current gain is set at $\beta+1$, but of course $\beta+1$ will change from about 20 when Tr_9 conducts to about 2000 when Tr_8 and Tr_{10} conduct.

The defining equations and their meaning are all given below.

- Setting amplifier input current to zero:

$$\frac{v_s-v_i}{R_s}+\frac{v_2-v_i}{Z_2}+\frac{v_1-v_i}{Z_1}=0$$

- Setting class A output current equal to $-G_m v_i$:

$$-G_m v_i=\frac{v_2-v_i}{Z_2}+\frac{v_2-e_o}{Z_3}+i_b$$

- If dumper output current is properly accounted for:

$$(\beta+1)i_b=\frac{v_1-e_o}{Z_4}+\frac{v_1-v_i}{Z_1}$$

- Using the currents in Z_3 and Z_4 to calculate e_o :

$$\frac{v_2-e_o}{Z_3}+\frac{v_1e_o}{Z_4}=\frac{e_o}{Z_L}.$$

Here there are six variables ($v_s, v_i, v_1, v_2, i_b, e_o$) and four equations, so three of our variables can be eliminated. Choosing to calculate e_o as a function of only v_s and i_b and manipulating gives

$$[(Z_1+Z_2+Z_3+Z_4)(Z_L+R_s+Z_LR_sG_m)$$
$$+(Z_1+Z_4)(Z_2+Z_3+Z_3R_SG_m)]e_0$$

$$=[(\beta+1)\left\{(Z_1+Z_2+Z_3+Z_4)R_s\right.$$
$$\left.+Z_1(Z_2+Z_3)-(Z_2Z_4-Z_1Z_3)R_sG_m\right\}$$

$$-\left\{(Z_1+Z_2+Z_3+Z_4)R_s\right.$$
$$\left.+(Z_1+Z_4)Z_2\right\}]Z_Li_b$$

$$+[(Z_1+Z_2+Z_3+Z_4)$$
$$-(Z_1+Z_4)Z_2G_m]Z_Lv_s \qquad \ldots(2)$$

which we write as

$$Ae_o=BZ_Li_b+CZ_Lv_s$$

where the coefficients A,B and C are represented by the expressions in square brackets †‡.

These equations are all linear, and it is good to pause awhile to ponder whether the distortion has been properly considered. The voltage across the dumpers V_2-V_1 will control i_b for the output $(\beta+1)i_b$ in a complex way related to the turn-on curve of the dumpers. In choosing to eliminate v_i and v_2, the distortion must appear in our equations as a distorted i_b which is not a copy of e_o or v_s. We deliberately chose to eliminate v_i and v_2 from our equations so that all the dumper distortion contributions to e_o occur in the single term BZ_Li_b. Now e_o can still be made rigorously proportional to v_s, if the large bracket B multiplying i_b can be set equal to zero for all signals. (The parameter β occurs *only* in the coefficient B in equation 2). The balance condition for the new equivalent circuit of Fig. 3 is thus $B=O$.

---

‡This is essentially a d.c. analysis of the circuit, and as such will remain valid only for frequencies low enough that time delay effects through the class A amplifier and bridge components can be ignored.

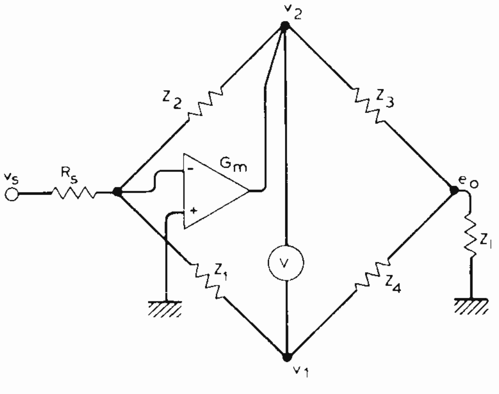


Fig. 2. *Simplified equivalent circuit showing that passive bridge balance can remove dumper voltage distortion.*

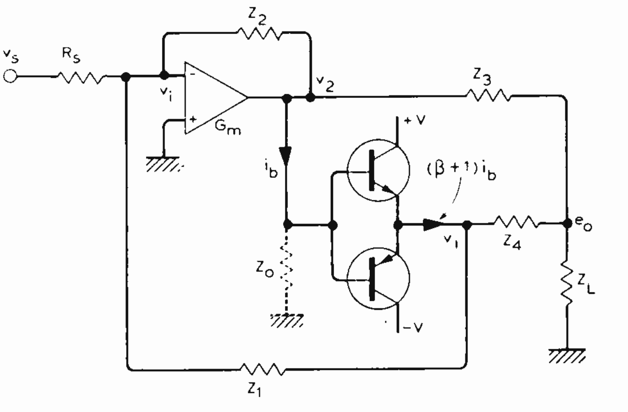


Fig. 3. *Equivalent circuit for more complete analysis, see box.*

quired for perfect bridge balance, and hence complete independence of the output from dumper distortion. A vital requirement that this be completely achievable in practice is that β be constant. (The extent to which non-constancy of β contributes to the presence of dumper distortion in the output is examined later.)

Thirdly, from equation (3), if G_m tends to infinity then the balance condition reduces to precisely the Walker condition $Z_2Z_4 = Z_1Z_3$ which appeared in the simple analysis of Fig. 1. So for large transconductance in the class A stage, the balance condition is precisely that obtained before. Moreover, Z_2 and Z_4 can be respectively capacitive and inductive without affecting our argument

Fourthly, we can now answer the claims by Olsson and others that the (non-linear) dumper input current i_b prevents the attainment of perfect bridge balance in the case of finite G_m. The analysis of Fig. 3 shows that no matter how non-linear i_b may be, if β is constant perfect balance can be achieved with finite G_m. Lest Fig. 3 is thought unrealistic, in that in practice a perfect current source is not available for the class A amplifier, we have made a more complete analysis. Taking into account the shunting effect of a load Z_o shown broken in Fig. 3 across this stage in any practical case, and we find that it has absolutely no effect upon the balance condition $B = 0$. The only effect of Z_o in equation (2) is to add further terms to the coefficient A of e_o, but it does not change the other coefficients. As a perfect current generator shunted by Z_o is equivalent to a voltage source with a finite output impedance, by including Z_o in Fig. 3 we have shown that balance *is achievable even with an imperfect class A stage*, provided β is constant and assuming Z_2 and Z_4 to be real.

Next, we must answer the question which we have thus far begged: To what extent will variations of β in the dumper stage (which certainly are present to considerable extent in the Quad 405 circuit, and at least to a certain extent in any realizable class B output stage) contribute to dumper distortion appearing in e_o through the incomplete cancellation of the term BZ_Li_b? From the balance equation (3) provided β does not fall too low and provided G_m is large, the effect of changing β will be small.

To quantify this conclusion, return to equation (2). Assume that β varies from say β_{min} to β_{max} as the dumpers operate. The dumper output current βi_b, denoted by I_D can be assumed to be constant to a first order approximation and independent of β in the operation of the circuit. If Δe_o represents the peak-to-peak distortion in the output signal e_o due to changing β in the dumpers, then

$$\Delta e_0 \approx \frac{\left\{(Z_1+Z_2+Z_3+Z_4)R_s + (Z_1+Z_4)Z_2\right\}\left(\frac{1}{\beta_{min}+1} - \frac{1}{\beta_{max}+1}\right)Z_LI_D}{(Z_1+Z_2+Z_3+Z_4)(Z_L+R_s+Z_LR_sG_m) + (Z_1+Z_4)(Z_2+Z_3+Z_3R_sG_m)}$$

This formula can be further approximated assuming (as in the Quad 405) that the bulk of the load current is furnished by the dumpers, so that $\bar{I}_D = e_o/Z_L$, and that Z_2 and G_m dominates the terms on the right-hand side. Then

$$\frac{\Delta e_0}{e_0} \approx \frac{(Z_1+R_s)\left(\frac{1}{\beta_{min}+1} - \frac{1}{\beta_{max}+1}\right)}{G_mZ_LR_s}. \qquad \ldots.(4)$$

This distortion has the shape of a half-wave-rectified sine wave. That due to changing dumper current gain can be reduced to insignificance by making β_{min} and G_m adequately large. This component of distortion then is being reduced by conventional feedback on account of the appearance of G_m in the denominator of equation (4). This distortion percentage is independent of the output signal provided it is large enough to cause both dumpers to operate and is also frequency-independent. We comment later on the possibility of removing such distortion entirely.

In the Quad 405, where approximately Z_1 is 500Ω, R_s 180Ω (R_{16} in the circuit diagram, Fig. 4 or ref. 1) Z_L 8Ω, β_{min} 20, and G_m 50,000A/V, the distortion expected due to changing β is of the order of 10μV peak or about 132dB below full output and hence negligible.

Further interesting conclusions can be drawn from equation 2. For instance, it can be shown rigorously that for large G_m, the output impedance of the amplifier is that of Z_3 and Z_4 in parallel. The voltage gain of the amplifier equivalent circuit e_o/v_s can also be shown to be approximately $-R_1/R_s$.

More interesting, perhaps, is an estimate of the effect of bridge unbalance on the output distortion. Returning to equation (2) to calculate the effect, Δe_o, on e_o of a change ΔZ_i of any *one* of the bridge impedances Z_1, Z_2, Z_3 or Z_4 (assuming Z_2, G_m large), and considering that the dumper notch distortion ($\Delta V \approx 1.5V$) results in a peak-to-peak fluctuation ΔI_D in I_D of approximately $1.5/R_3$ amps then

$$\Delta e_0 \approx \frac{1.5Z_1}{Z_2} \cdot \frac{\Delta Z_i}{Z_i}.$$

The dumper distortion voltage approximates a square wave of amplitude 1.5 volts, whose transition time is determined by the signal frequency and amplitude, the dumpers and Z_4. Our formula for bridge error shows that if $Z_2 = 1/j\omega C$, then the distortion seen from bridge unbalance will be the time derivative of this, which would appear as sharp spikes whose amplitude depends directly on the speed of the transition.

Further thoughts

Recapitulating on the operation and analysis of the current dumping amplifier, the dumpers produce a distortion voltage which is completely removed by a balance condition which approximates to $Z_1Z_3 = Z_2Z_4$, and which becomes progressively less dependent on the gain G_m of the class A amplifier as it is made large. A second kind of distortion is the asymmetry of the dumper current gain, and any non-linearity of this gain with signal. This current distortion cannot be balanced out, and its effects vary as $1/G_m$, so they are reduced by conventional feedback. In the Quad 405 amplifier this distortion appears to be low but perhaps not negligible.

In electronics, the concept of duality allows a voltage source to be transformed to a current source and vice versa. We feel it is possible that a bridge configuration exists such that the current distortion can be nulled as well as the voltage distortion. It may be possible to superimpose the two bridges with one class A amplifier. We have devised several theoretical methods for removing current distortion entirely, maintaining the normal bridge components, by applying positive current feedback to the class A amplifier to give it zero output impedance. The value of β then disappears from the analysis. However, the amount of feedback required depends on G_m. We feel a better solution is possible and challenge the readers of this journal to produce one.

Results of measurements will appear in part 2.

References

1. Walker, P. J. Current dumping audio amplifier. *Wireless World* vol. 81, December 1975. pp. 560-562.
2. Letters to the editor. *Wireless World* vol. 82, April 1976, pp. 54-55.
3. Letters to the editor. *Wireless World* vol. 82, July 1976, pp. 60-62. ☐

BOOKS RECEIVED

Small Craft Radar by John French. Although this publication is primarily of interest to small craft users, anyone, technically qualified or not, who is interested in radar will find the book interesting. The first two chapters cover the evolution of small radars and their principle. Operation and interpretation are then described with the help of numerous radar display photographs. Final chapters discuss the practical use of radars, their installation, and fault finding. Price £4.50 hardback, pp.207. Stanford Maritime Ltd, 12 Long Acre, London WC2E 9LP.

Cable television by John E. Cunningham is a practical guide aimed at engineers and technicians who want a working knowledge of c.t. systems. The book is an American publication. Price £8.35 paperback. pp.352. Prentice Hall International, 66 Wood Lane End, Hemel Hempstead, Herts.