Appendix. Stability analysis of error feedback including equivalent topologies

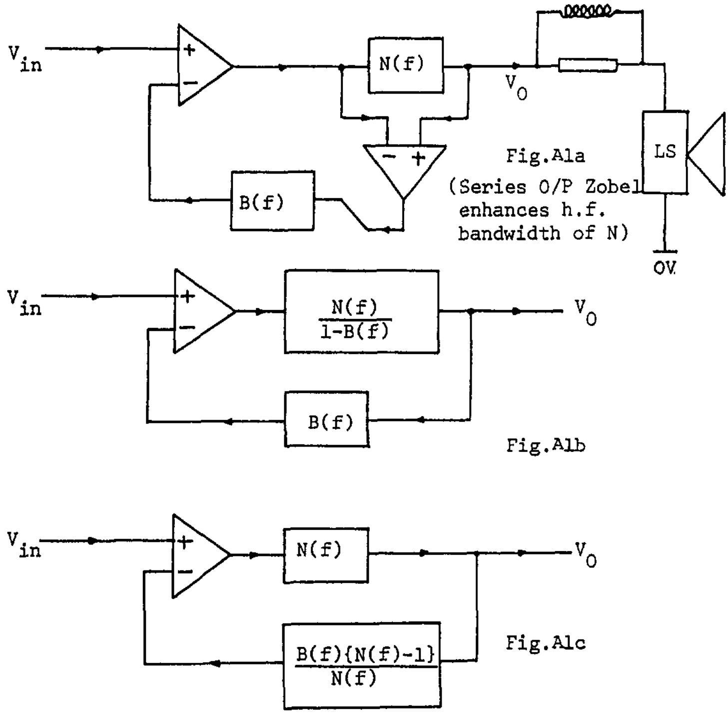

Figure A1 - Equivalent error feedback configurations

By analysis the closed loop gain G(f) and loop gains, $H_1(f)$, $H_2(f)$, follow, where:

$$G(f) = \frac{N(f)}{\{1-B(f)\}+B(f)N(f)} \quad \text{..... A1}$$

$$H_1(f) = \frac{N(f)B(f)}{B(f)-1} \quad \text{..... A2}$$

$$H_2(f) = B(f)[1-N(f)] \quad \text{..... A3}$$

It is interesting to compare the system in Figure A1b with Figure A1c. In the former we ideally require infinite gain in the forward path ($B(f)\approx 1$) whereas in the latter we have zero gain in the feedback path ($N(f)\approx 1$), yet both generate the same closed loop gain. On an initial consideration Figure A1b appears impractical whereas Figure A1c would appear eminently acceptable.

However, if we test for instability by equating the loop gain to unity then both equations A2 and A3 result in the condition:

$$B(f)[1-N(f)] = 1 \qquad \ldots\ldots A4$$

(for oscillation).

The output stage N(f) is, within the context of a power output stage, a near unity gain amplifier (e.g. a complementary emitter follower output stage with local negative feedback through emitter degeneration). However, the transfer function of N(f) will depend upon the load impedance (loudspeaker). For good control of the closed loop gain it is desirable to maximise the bandwidth of N(f). Basically this will be limited by the f_T of the output transistors, however, by use of a series output Zobel network see Fig.A1a, (and/or feedforward across N(f)) the bandwidth can be extended such that to a good approximation,

$$N(f) = \frac{N_0(1 + j\frac{f}{f_3})}{(1 + j\frac{f}{f_1})(1 + j\frac{f}{f_2})} \qquad \ldots\ldots A5$$

The error amplifier can then be designed using wide bandwidth circuitry with local negative feedback and compensation (see circuit diagram in Fig.5.1) such that B(f) is a well defined first-order network where:

$$B(f) = \frac{B_0}{(1 + j\frac{f}{f_4})} \qquad \ldots\ldots A6$$

Generally $f_1 \approx f_T$ where f_3, $f_4 > f_1$. We also note that B_0 is close to unity, though in analysis account must be taken for values ranging, say, from 0.8 to 1.2 for stability and amplitude peaking under conditions of poor adjustment. From equations A4, A5 and A6 we deduce the following criteria for loop stability:

Let f_n be the natural frequency of oscillation at unity loop gain;
N_L the lower bound to N_0,
N_u the upper bound to N_0.

1. For dc instability ($f_n = 0$)

$$N_L = \left(\frac{B_0-1}{B_0}\right) \qquad \ldots\ldots A7$$

2. For ac instability ($f_n > 0$)

$$f_n = \{f_1 f_2 (1+N_0 B_0 \frac{f_4}{f_3}) + f_4(f_1+f_2)(1-B_0)\}^{\frac{1}{2}} \qquad \ldots\ldots \text{A8}$$

$$N_u = \left[\frac{ (\frac{f_1+f_2}{B_0 f_4}) \left[1+ \frac{f_4^2}{f_1 f_2} (1-B_0)\{(1-B_0) + (\frac{f_1+f_2}{f_4})\} \right] }{ \left[1- \frac{1}{f_3} \{f_4(1-B_0) + (f_1+f_2)\} \right] } \right] \qquad \ldots\ldots \text{A9}$$

Conditions for stability:

Condition A $\quad N_u > N_L$

Condition B $\quad N_L < N_0 < N_u$

Condition C $\quad$ If $f_4 \to \infty$ then $f_3 < \left[\frac{N_0 B_0}{(B_0-1)(\frac{1}{f_1} + \frac{1}{f_2})} \right]$, $(B_0 > 1)$

In practice, N_0 is just less than 1 (although it can be non-linear) and $(1-B_0) = 0$ to minimise distortion. For optimum performance it is important to maximise f_3 and yet keep high frequency peaking in the closed loop gain to within tolerable bounds. As an example, the following results are computed for a simulated example where:

f_1 = 1MHz, f_2 = 20MHz, f_3 = 5MHz

Table of Results ($P(N_0=x)$ => max. gain at $N_0 = x$).

f_4 MHz	$B_0=1$ ($N_L=0$)			$B_0=1.2$ ($N_L=0.17$)		
	$f_n(N_0=1)$ MHz	$P(N_0=0.8)$ dB (approx)	$P(N_0=1)$ dB (approx)	$f_n(N_0=1)$ MHz	$P(N_0=0.8)$ dB (approx)	$P(N_0=1)$ dB (approx)
1	4.90	1.1	1.9	4.54	2.3	2.9
5	6.32	2.8	3.2	4.80	8.2	7.0
10	7.75	3.1	3.2	5.10	14.5	11.2
20	10.00	3.1	3.0	5.66	21	18.5
40	13.42	2.9	2.7	6.63	21	17.8

The results suggest that providing the bandwidth of N(f) is maximised then stability problems are minimal (practical circuit designs also corroborate this conclusion).