New Phase-Splitter

IMPROVED HIGH-FREQUENCY RESPONSE

By A. R. BAILEY *, M.Sc.(Eng.), A.M.I.E.E.

IN the past many phase-splitters have been investigated and the reader would be quite justified in asking why a further circuit has been developed. The answer is quite simple in that the performance of high-fidelity amplifiers may be no longer limited by the output-transformer but by the response of the phase-inverter. With the best transformers available this is very true, and the improvement in amplifiers performance that is obtained by using better circuits is quite startling.

In order that the reasons for discarding the present circuits may be seen, it is essential that all the requirements of the phase-inverter be first evaluated.

The first requirement of all phase-inverters is that they should deliver an output that is balanced to within a few per cent and does not alter as the valves age in use. Most of the phase-inverter circuits in use have this property, but the paraphase-inverter (Fig. 1) does not, as there is no negative feedback to stabilize the gain of the stage.

The second requirement is that the output-impedances from both halves of the phase-splitter should be approximately equal. The reason for this is nothing like so obvious at first sight. In fact there are two reasons for this requirement. The first is that severe grid-blocking can occur if the amplifier is accidentally over-driven (ref. 1). This can be overcome by using high-value grid stoppers but this gives an additional high-frequency time-constant due to the input capacitance of the following stage. As will be mentioned later, this gives a very undesirable tendency to h.f. oscillation when high values of negative-feedback are applied. The second disadvantage is that the drive to the two output valves may unbalance severely at high frequencies due to the different time-constants produced. This will have the effect of severely limiting the h.f. power available and will also increase the h.f. distortion. The two circuits that suffer from this drawback are the floating paraphase (Fig. 2) and the concertina (Fig. 3). In both circuits the valve loads that drive the output stage are balanced, but unfortunately the output impedances are not balanced. This is due to the voltage negative-feedback inherent in the circuits. This negative-feedback overcomes the problem of valve ageing mentioned before, but brings the disadvantages that have been just mentioned. In addition, these circuits are not readily d.c. coupled to the previous stage. This is a severe disadvantage where large amounts of feedback are contemplated, as the additional low-frequency time-constant of a further coupling capacitor can easily cause instability at low frequencies.

Up to the present it seems to have been generally assumed that these were the only circuits to be avoided, if at all possible. Unfortunately this has proved not to be the case and the cause of the distressing tendency of high-feedback amplifiers to go unstable can often be laid at the door of the phase-splitter. The reason is quite simply one of poor h.f. response. A poor h.f. response in the phase-splitter will cause a falling loop gain, but what is more important it will also give a phase shift that tends towards 90 degrees retard. Now, if there is a total of 180 degrees retard at some high frequency, the

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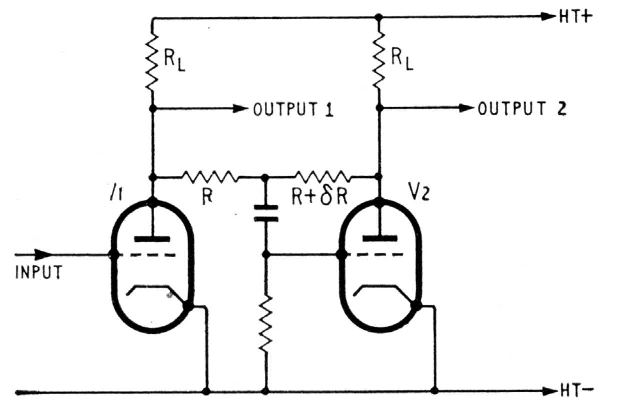


Fig. 2. Basic circuit of "floating" paraphase phase-splitter.

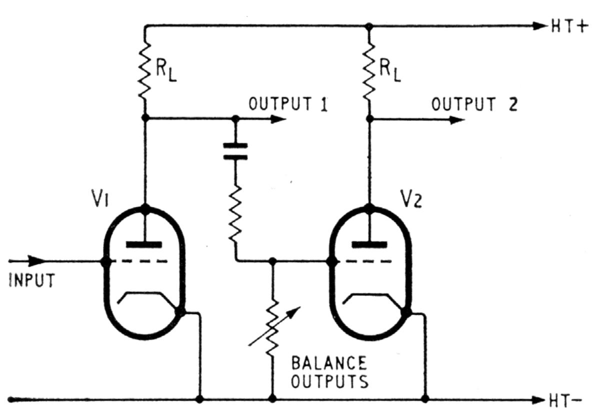


Fig. 1. Basic circuit of paraphase phase-splitter.

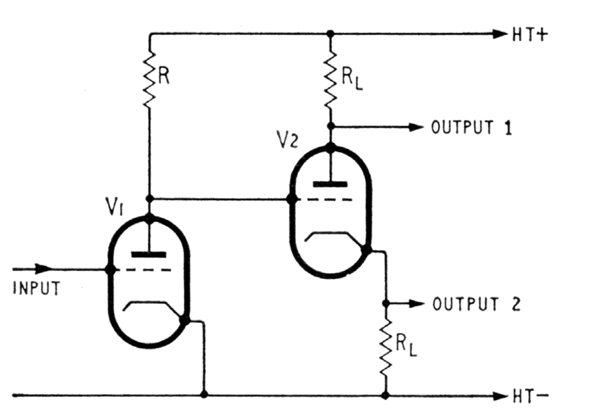


Fig. 3. Basic circuit of direct-coupled concertina phasesplitter.

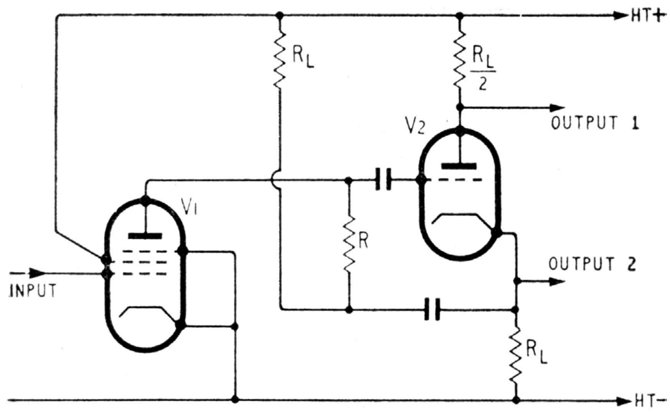


Fig. 4. Basic circuit of jeffery's high-gain phase-splitter.

feedback will no longer be negative but positive. If the gain round the amplifier loop exceeds unity at this frequency then the amplifier will oscillate. Even if the loop gain is below unity then the amplifier may go unstable with even quite short leads to the loudspeaker due to the capacitive loading placed on the amplifer. Indeed it has been stated by Crowhurst (ref. 2) that the effect of near instability is quite audible and the amplifier gain margin should be at least eight times if this effect is to be inaudible.

For this reason it is essential that all phase shifts that can be removed should be removed : either completely, or at least as far out of the way as possible. Here it might be well noted that the use of grid stoppers in feedback amplifiers is to be deplored unless they are absolutely necessary. Many parasitics have been caused rather than stopped by them!

Two circuits that suffer from excessive h.f. phase shift are shown in Figs. 4 and 5. Fig. 4 shows the circuit due to Jeffery (ref. 3) and it is unnecessary to go into the details of the phase shift in this circuit again. The interested reader is referred to the correspondence following the publication of a subsequent article (ref. 4).

The circuit shown in Fig. 5 is well known and widely used but the fact remains that its h.f. response is relatively poor. This cannot be due to the second half of the valve as this section is effectively driven as a grounded-grid amplifier. The trouble is due to the first half of the valve and is due to that hardy perennial—Miller effect. The gain of this first valve is effectively halved due to the input impedance at the second valve cathode. Even so the Miller capacitance is quite large and certainly cannot be neglected. In order that some estimated value of frequency response can be obtained, some typical values will be taken. Using the ECC83 as a typical valve, the quoted anode-to-grid capacitance is 1.6 pF so the total value will be certainly as large as 2.0 pF when wiring and base capacitances are taken into account. The gain of each half of the valve can be as much as 60 times, but this would be better reduced to a factor of 50 as there is a supply voltage loss in the common-cathode resistor. The overall gain will therefore be about 25 times when used in this phase-splitter. This will give a reflected Miller capacitance of approximately 50pF, so the total capacitance loading on the previous stage will be about 60 pF if 10pF is allowed for all other capacitances. With a 100 kΩ source impedance this will give a −3dB point at about 25kc/s, and this is clearly not good enough when output transformers with primary resonances of about 150 kc/s are considered. The phase shift of the amplifier circuits must be as small as possible where the output transformer reaches its first primary resonance; and therefore the bandwidth of this type of phase-splitter can easily degrade the total amplifier performance. The use of a step network across the anode load resistor of the driving valve can help in this matter, but only if the step starts well before the natural fall-off frequency of the circuit itself. In the case just considered this would mean starting the fall-off of amplifier gain by the step network at approximately 2.5 kc/s or lower. This would obviously give excessive reduction in loop gain at the high frequencies, with consequent increase in distortion.

The answer therefore lies in producing a fall-off at the h.f. end of the spectrum that starts at a much higher frequency. This could be attempted by reducing the value of the output impedance of the previous stage. This could be done by negative feedback with consequent gain loss; or alternatively by using a smaller value of anode load resistor. This latter also gives a severe loss in gain, quite apart from the increased noise that is produced by the increased valve current. The answer was therefore seen to lie in producing a phase-splitter that did not give the large input capacitance of the previous circuit.

Circuits are known (e.g. ref. 5) that do give good h.f. response in phase-splitter service, but they suffer from high cost due to the complexity of the circuitry involved. The circuit that was finally evolved (Fig. 6) has a cost that is only slightly more than that of

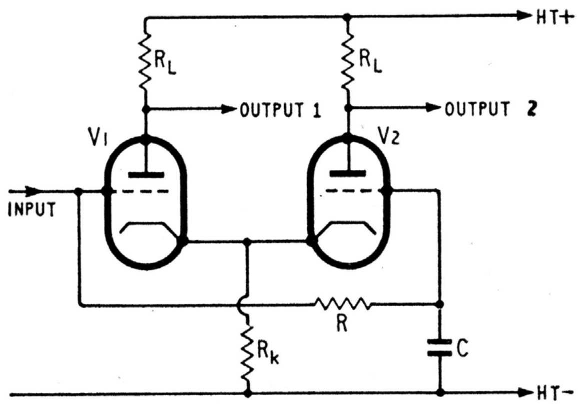


Fig. 5. Basic circuit of long-tailed-pair phase-splitter.

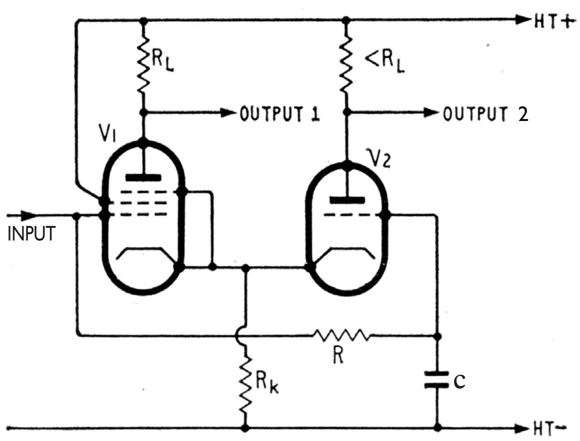


Fig. 6. Basic circuit of modified long-tailed-pair phase-splitter.

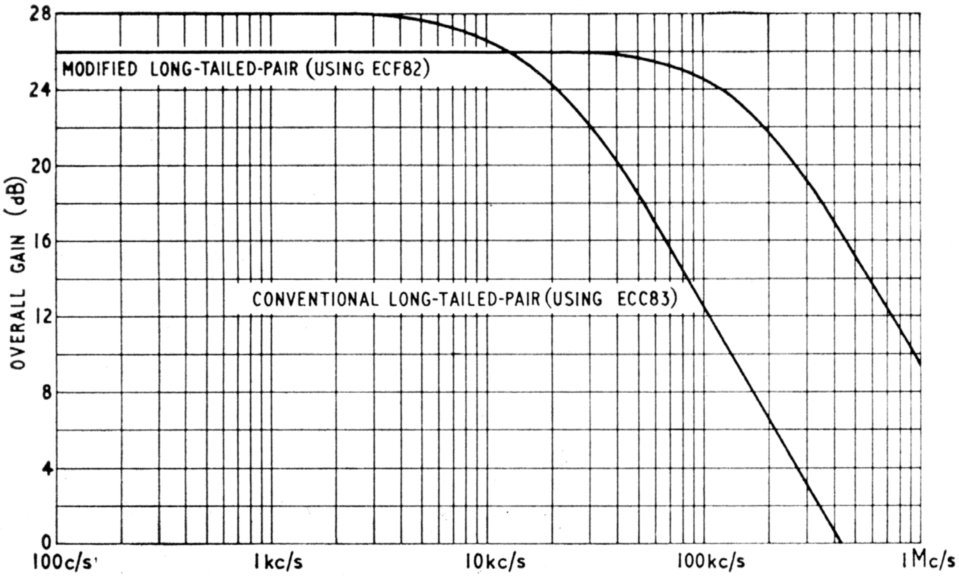


Fig. 7. Relative gain/frequency response curves of original and modified long-tailed-pair phase-splitters.

This has a built-in 3:1 low-frequency step network which improves l.f. stability, and a 20:1 h.f. step network. The h.f. network may need component values altering for different types of output transformer due to the wide variation in resonant frequencies and other parameters.

This circuit was originally developed for improving the performance of the Radford MA12 and MA15 amplifiers and certainly did this to great effect. Equally there is no reason why the circuit should not give a considerable improvement in the stability of other amplifiers using good output transformers. The circuit is simple and stable and has no difficulty in providing drive for the largest output valves.

the conventional circuit, but has a greatly improved response at high frequencies.

The operation of the new circuit is just about identical with that of the conventional long-tailed pair except that the first valve is a pentode. This reduces the Miller effect to negligible proportions and increases the total bandwidth by a factor of just under ten times. Even allowing that the gain of the circuit is about 2 dB less than the conventional circuit, this still gives a gain/bandwidth improvement of about seven times. The comparative gain/frequency plots are shown in Fig. 7, where it is seen that the final rate of fall in both cases is identical at 20 dB per decade. This indicates an ultimate phase shift of 90 degrees which was borne out by measurement.

Owing to the partition of valve current in the pentode, the anode load resistor is made somewhat greater than that of the triode stage so that a balanced output is obtained. The circuit can be d.c. coupled to the previous stage as can the usual one, and a complete "front-end" for driving the output valves of an amplifier is shown in Fig. 8.

A double-pentode having video amplifier characteristics and low input capacitance would enable greater overall gain to be obtained, but so far the author has not been able to find a valve with suitable characteristics. If such a valve were available, then the overall gain could be increased by a factor of about four times. Where sufficient spare stability margin was available this could lead to a further reduction in the distortion of the amplifier in use.

REFERENCES

1. High Fidelity Sound Engineering, by N. H. Crowhurst (Newnes), p. 130.

2. Why do Amplifiers Sound Different, by N. H. Crowhurst, *Radio and Television News,* March 1957.

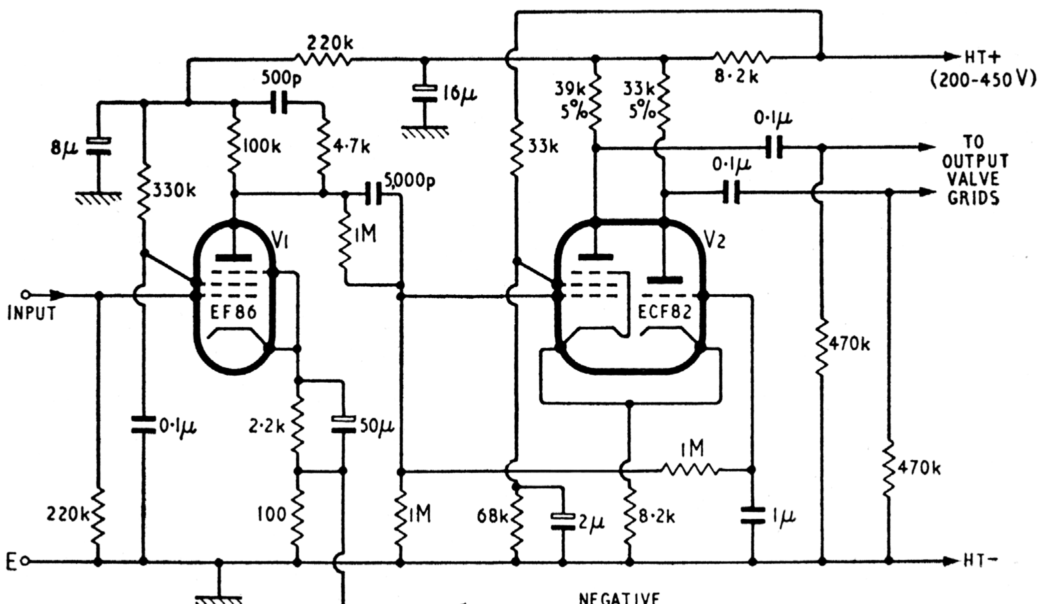
3. Push-Pull Phase-Splitter, by E. Jeffrey, *Wireless World,* August 1947, p. 274.

4. Economical High-Gain A.F. Amplification, by Arthur R. Bailey, *Wireless World,* January 1960, p. 25, (*Letters*) March, p. 133, April, p. 181, May, p. 244.

5. The New "Isodyne" Phase-Splitter, by E. F. Worthen, *Audio,* August 1958, p. 26.

Fig. 8. Circuit of complete pentode amplifier and phase-splitter for use in a high-fidelity amplifier with a large amount of negative feedback.

October 1962 correction applied



LETTERS TO THE EDITOR

The Editor does not necessarily endorse opinions expressed by his correspondents

New Phase-Splitter

I READ with interest Mr. A. R. Bailey's article "New Phase-Splitter" in your September issue. I believe, however, that his circuit could be further improved by simple modifications.

The ratio of screen to anode current in a pentode varies somewhat from valve to valve, and also in the same valve in different parts of its characteristics. Negative feedback applied to the cathode of a pentode as in V1 of Mr. Bailey's Fig. 8 tends to ensure that the signal component of the cathode current is a faithful replica of the input signal. It would appear better to arrange the feedback so that the signal component of the anode current only is forced to follow the input signal. This can be done by removing the signal component of the screen current from the cathode resistor, i.e. by returning the screen decoupling condenser to the cathode instead of to earth. A similar argument could be applied to V2. This qualitative argument is admittedly inadequate to decide which arrangement would in fact give less distortion, and since it appears from inspection of the published characteristics of the EF86 that the screen current is a more linear function of the grid voltage than is the anode current, there is probably little to choose between the two arrangements on grounds of distortion alone.

If, however, the screen decoupling condensers of both V1 and V2 were returned to their respective cathodes as suggested, two other advantages would result:

(1) The input capacity of V1 would be very substantially reduced, since the signal potential of the screen as well as that of the cathode, would approximate to the grid signal potential. The input capacity of V2 would also be somewhat reduced.

(2) A balanced output would be obtained when the two anode loads of V2, were made equal instead of slightly unequal, moreover the balance would be less upset if valves of varying screen-to-anode current ratio were used for V2.

Bristol, 8. D. F. GIBBS
H. H. Wills Physics Laboratory,
University of Bristol.

I WAS much interested by Mr. Bailey's article on phase-splitters in your September issue. The long-tailed pair circuit described has many advantages but there is a rather odd snag that came to light in the course of developing a special amplifier using the more usual double-triode variation.

I found a very intractable hum in my amplifier. This was eventually traced back to the h.t. rectifer which was choke-fed.

At the instant of conduction the transformer waveform is distorted and this results in a high-frequency pulse appearing in the heater circuit. Because of the high impedance in the cathode circuit of the phase-splitter this pulse can appear across the load via the heater-cathode capacity.

The effect is almost undetectable if the more usual capacitor-input rectifier circuit is used. A cure for it is the use of a separate heater transformer for this and other cathode-coupled stages.

With a choke-input filter the resultant hum (if this is the right term) is otherwise unacceptable but with a capacitor-input filter it may pass as background noise. However, an improvement in this can result from feeding any cathode-coupled stages from a separate heater transformer.

Swindon. T. S. MARSHALL

I SHOULD like to discuss one or two points arising from Mr. A. R. Bailey's article on a "New Phase-splitter" in the September issue.

(1) Can we safely establish the pentode and the triode at reasonable working points with the wide range of supply voltage quoted? I suspect that we may find the triode held very near cut-off. Certainly I am sure that there is no hope of getting the even-harmonic balance we get with a twin triode.

(2) The statement attributed to Crowhurst is a description of something which is obvious if stated more formally. Near instability implies that $(1-\mu\beta)$ in the gain expression $\mu_f = \mu/(1-\mu\beta)$ is not the large number we usually have but corresponds to the positive feedback in the region near the Nyquist point. With a 6dB gain margin, for example, $(1-\mu\beta) = \frac{1}{2}$ and the distortion of the basic amplifier at the 180° frequency is doubled. The feedback must be negative and maintamed negative and high to the limit of audibility: the Duerdoth margin is a good guide.

(3) The long-tailed pair usually implies a high heater-cathode voltage. I prefer to raise the heated line to about +20 volts so that the first stage heater-cathode diode is biased into cut-off and heater emission cannot contribute to the current in the cathode resistor which is, so often, part of the feedback path. This reduces the stress on the l.-t. pair and also gives some improvement with some valves. There is a lot to be said for using an n-p-n transistor as the common cathode, resistor to give, since it can be in the common-base mode for a.c., a very high coupling impedance combined with low voltage drop.

I should be tempted to examine whether the pentode triode working points could be tied together by the sort of technique used in establishing the working conditions of starved amplifier, were it not for Mr. Bailey's Fig. 8. It is instructive to compare this with the circuit described by W. A. Ferguson in the May and June 1955 issues of *Wireless World*, in which an EF86 drives an ECC83 phase-splitter. (Fig. I p. 280 June 1955). As a point of detail, the EF86 screen is there decoupled to the cathode, but it is the anode circuit which is particularly revealing.

(4) Most circuits use a 100kΩ anode load for the EF86 and a 4.7kΩ resistor to give a 20:1 step. The difference between the two circuits is that Mr. Bailey uses a 500pF capacitor, whereas Mr. Ferguson used one of 47pF. Mr. Bailey has been worrying about the Miller effect at 25kc/s. Then he introduces a step circuit which is 3dB down at $\omega CR = 1$ with $C = 500 \times 10^{-12}$ and $R = 100{,}000$, so that $\omega = 2.104$ or around 3,000c/s. At 1200c/s he has about 75° contributed by this step circuit and has lost 12dB of his gain, and of his feedback. Moreover, at 25c/s his source impedance to the grid of the l.-t. pair is getting down towards the 4.7kΩ and if the overall response is sketched out it becomes apparent that the ECC83 Miller effect will begin to show some influence only in the region of 200-400kc/s. By this point, however, we are concerned with a whole lot of other factors like the CR response at the anodes of the l.-t. pair and the amplifier is, to use a metaphor painful to transistor circuit designers, back in the melting pot.

The loop characteristics of the 1955 circuit confirm this treatment and show that it is quite practicable to have

20 dB of feedback left (from 30dB) at 30,000c/s. They also show, in textbook style, a positive feedback defect at the low frequency end, although it will be rare for us to be troubled by this 2c/s effect and easy to overcome it.

If it were necessary we could make use of a number of positive feedback tricks to reduce the effective input capacity of the l.-t. pair. The capacitance from A2 to G1 is obvious, but a capacitance from A1 to G2 with a 4.7 kΩ resistance in the G2 lead is an interesting variant which might repay study. However, if we use a step circuit, and since we shall need at least one we can do this, at the input to the phase-splitter the Miller effect is one of the least of our worries.

London, W.8. THOMAS RODDAM

IF Mr. Bailey cares to connect a 2pF capacitor from V2 anode to V1 grid in his circuit of Fig 5 he will find that the high-frequency disadvantages he mentions are eliminated.

Another place where neutralization is usually effective is in the output stage itself where, even when pentodes are used, a 1pF anode-grid capacitance is not uncommon. In this case a series 30-20kΩ resistor will prevent possible r.f. instability.

Woodford Green, Essex. P. A. DOUVALETELIS

IN his article in the September issue, Mr. A. R. Bailey states that the Concertina Phase Splitter suffers from unbalance at high frequencies due to the different output impedances at the anode and cathode.

It has been shown in this journal in a previous article (W. T. Cocking, Feb., 1948, p. 62) that provided the anode circuit and cathode circuit load impedances are equal in this circuit, the voltage outputs are equal. This is clear when it is realized that the anode current flows through both these circuits in series. Thus even at high frequencies where the circuit capacitances cannot be neglected, no voltage unbalance will occur with the usual circuit arrangements. The two outputs will fall off with " break point " frequencies

$$\frac{1}{2\pi R_L C_k} \quad \text{and} \quad \frac{1}{2\pi R_L C_a} \quad \ldots \ldots \quad (1)$$

where C_a is the anode–earth circuit capacitance and C_k is the cathode–earth circuit capacitance.

If $C_a = C_k$ (as it usually is since the major part of the capacitances consist of the grid-cathode capacitances of the following identical stages) the two outputs fall from the same frequency, remaining balanced. A calculation of the break point frequencies using the formula (1) shows that for typical values (100kΩ, 20pF) a frequency of order 100kc/s is obtained.

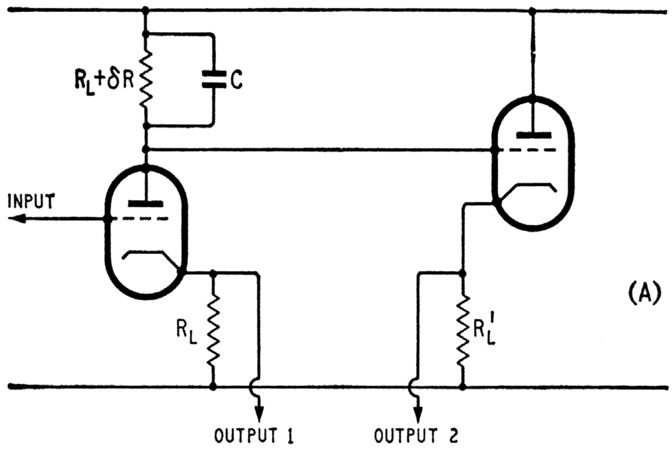
A further advantage of the concertina circuit is that it can be readily direct coupled to the previous stage (as shown in Mr. Bailey's article (Fig. 3)).

Analysis shows that Miller effect is negligible and there is a very high input impedance at the grid of the phase-splitting valve.

(Input impedance is approximately $2C_{ag} + C_{gk}/\mu$ which is approximately $2C_{ag}$ with the usual meaning for the symbols. As C_{ag} is of order 3pF for a triode, $2C_{ag}$ is usually negligible in comparison with the anode-earth capacitance of the previous stage.)

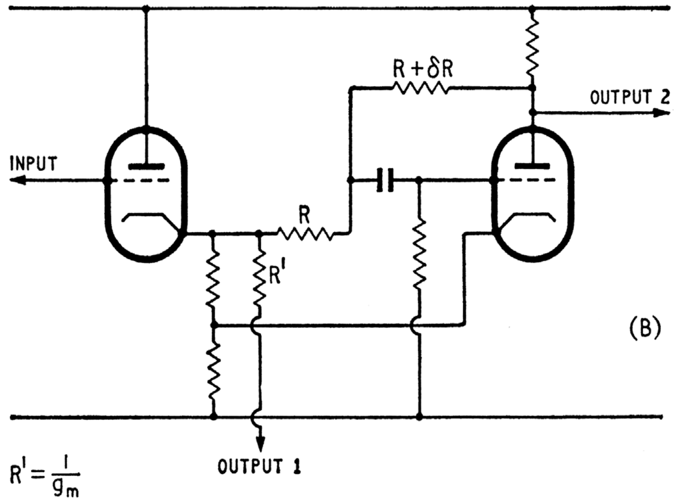
If it is desired to obtain equal output impedances then equal *low* output impedances can be obtained by using a cathode follower following the anode circuit, as shown in the accompanying diagram (A). This circuit will provide equal very low output impedances (of order 100Ω). The two outputs will remain balanced at high frequencies whilst the low output impedance is also of advantage in reducing the effects of " grid blocking. "

Mr. Bailey's article contains similar comments about the " floating " paraphrase phase splitter (Fig. 2 of the original article). Equal output impedances with very high impedance and no Miller effect can be obtained in this circuit with good balance at high frequencies by using a cathode follower as the first valve and (if it is required to have equal output impedances) a resistor in



$$\frac{R_L + \delta R}{R_L} = \frac{\mu + 1}{\mu}$$

C = CAPACITANCE IN PARALLEL WITH OUTPUT 1.
R_L' CHOSEN TO GIVE EQUAL CURRENTS IN BOTH TRIODES.



$$R' = \frac{1}{g_m}$$

the output of the cathode follower to equalize the output impedances (B). Again very low output impedances are obtained. (Output impedance approx. 2/gm) of order 100Ω.

These circuits are thus capable of providing most of the advantages claimed for Mr. Bailey's circuit whilst at the same time providing a lower output impedance. Mr. Bailey's circuit does however have the advantage of a higher gain.

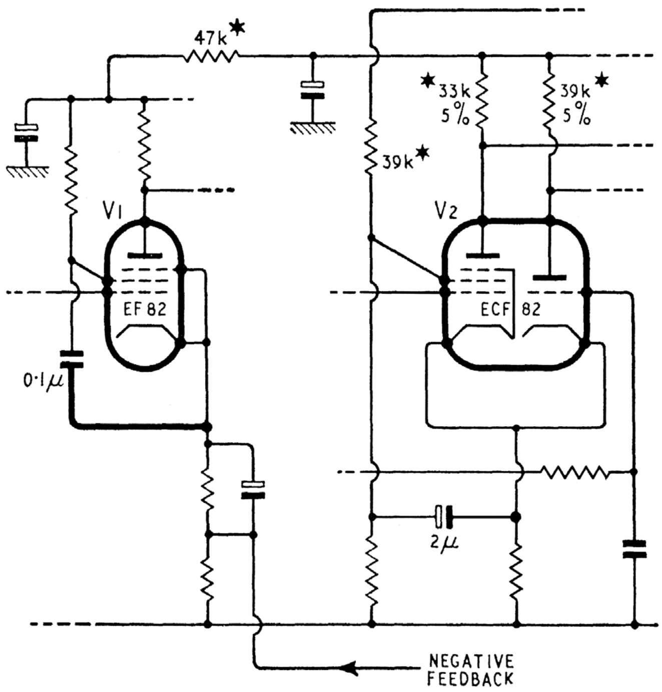
Cardiff. P. WILLIAMS
Department of Applied Physics,
Welsh College of Advanced Technology.

The author replies:-

IN replying to these letters I would first like to thank Mr. Gibbs for his helpful comments. I have tried returning the screen decoupling capacitors to their respective cathodes and there is an improvement as he predicts. In view of the advantages to be gained I would suggest making the modifications to the original circuit shown in the accompanying diagram, in which asterisks indicate altererd values.

The bandwidth is slightly increased to 190 kc/s and the distortion is definitely reduced for large output swings. The effect of these two is barely noticeable on the overall amplifier performance but the balance obtained is far better for valves made by differing manufacturers. This enables the output valve distortion to be held to a minimum.

I was interested in Mr. Marshall's comments on choke-input filters Luckily, however, the capacitor input filter is normally cheaper and therefore preferred.



In addition the input choke usually hums audibly due to magneto-strictive effects. Nevertheless it is a warning that is well worth bearing in mind.

Turning now to the letter from Mr. Thomas Roddam, I think that it will be preferable to deal with each of his points in turn.

(1) This may be due to a misprint (mine) that was corrected in the last edition of *Wireless World*. With the correct value of 220 kilohms for the anode feed resistor of V1 (or using the modified circuit just given) the two d.c. anode potentials of the phase-inverter balance to within 10 volts over the range of h.t. supply quoted. The distortion of the original circuit was far outweighed by that of the output valves and the distortion of the modified circuit is even lower.

(2) Unfortunately the matter is not quite as simple as Mr. Roddam would lead us to believe. The effect of near-instability that is well into the supersonic region can apparently be detected aurally. This subjective effect can be heard with amplifiers that have an impeccable performance within the normally accepted audio band of frequencies. I am not at all certain of the reason for this, but I would expect that the findings of D. L. Pimonow (reported in *Wireless World*, October 1962, p. 493) would have some bearing on the matter.

(3) I agree about the desirability of a positive bias on the heater-chain but feel that the addition of a n-p-n transistor and its associated components is unnecessary for an audio amplifier. There could easily be cases where such a circuit would have positive advantage but I do not think that this is one of them.

(4) In fact the circuit used commercially has a 40 to 1 step and uses a 2.7 kilohm series resistor. The 4.7 kilohm value was quoted in the article to allow for transformers of a lower resonant frequency. The step has been started fairly low down to obtain a high stability margin. If it is felt that a reduction in the h.f. distortion is preferable to the increased stability then the capacitor could be reduced to 250 pF and the series resistor increased to 10 kilohms.

Incidentally the loop gain of the Ferguson amplifier, referred to by Mr. Roddam, has fallen by 4 dB at 12 kc/s. This is more than would be expected from the values of the step network and the extra amount fits in with the predicted Miller capacitance.

I would definitely disagree with Mr. Roddam when he states that Miller effect is one of the least of our worries. "Know thy phase-shifts" has been my motto for feedback amplifiers and has always stood me in good stead. Once the transformer resonant frequency is reached there is then a severe overall phase retard. The step-network should have finished by this point or it will be adding further phase retard. An additional phase retard due to Miller effect in the phase-inverter can then well take the feedback loop close to instability even if not actually causing it. The effect of a capacitive load across the output further aggravates the matter, and it is well known that few amplifiers can stand appreciable capacitive load without instability.

If, however, the additional phase-shift due to Miller effect is absent, then the gain and phase margins can be made far better. One certainly cannot disregard phase-shifts about 400 kc/s; the gain margin of the amplifier in which this circuit is used is -26 dB but occurs at a frequency of 2.7 Mc/s. The phase margin is 90 degrees. Such performance could not be obtained with the normal long-tailed pair.

The last point is the use of positive feedback to remove the Miller effect. This is mentioned by both Mr. Roddam and Mr. Douvaletelis and was in fact the first thing that was tried in an attempt to improve the performance. (Hi-Fi News, July 1962, p. 90). Unfortunately it only made matters worse. This was traced to the unbalance in the input impedances of the output valves at high frequencies. This unbalanced loading of the phase-splitter causes unbalance in the drive to the output valves and consequently removes the neutralizing. The same is the case with neutralization of the output stage. So far I have found no advantage to be gained by neutralization and even if it could be made to work it would render the amplifier performance very susceptible to component changes.

So far as improvement in performance of amplifiers is concerned, the proof of the value of a modification is in the results obtained. By using this circuit it is possible to apply far more feedback without instability. With high resonant frequency transformers this improvement has been in the region of 15 to 17 dB. This, to me, seems to be a very worthwhile improvement.

ARTHUR R. BAILEY

Note the reference above from the article 'Push-Pull Input Circuits' by W. T. Cocking in *Wireless World* Feb. 1948 which can be found @ www.keith-snook.info

Cocking shows that provided the anode and cathode load impedances (*including R_k and R_a and the grid impedances they feed*) are equal the voltage outputs will be equal even at high audio frequencies despite the cathode output impedance being very low due to 100% negative feedback and the anode r_a being very high due to the large un-decoupled cathode resistor. Cocking's work was ignored by Morgan Jones (*although he did credit other prior art*) in his rambling in *Wireless World* Jan. 1996 which can be found at www.keith-snook.info. Hardly a fresh look at valve power.

Comments by Jones and others about high cut-off and balanced dominant poles are misleading. The best practice for low intermodulation distortion (*the distortion that valve amps handle well*) is to place a dominant pole in or before the first stage and ensure that subsequent stages have increasing wider bandwidths. Output transformer bandwidth (and transfer function) determines all that precedes it and series resonance giving a 180° phase shift to the negative feedback can often occur at frequencies as low as 40kHz with peaks in the open loop response higher than the 1kHz level, making feedback calculations based on constant A_0 and wide band phase splitters meaningless.

Also achieving perfect balance at the phase-splitter and or push-pull output stage may not be desirable if even harmonics are cancelled leaving relatively higher level odd harmonics.

KEITH SNOOK