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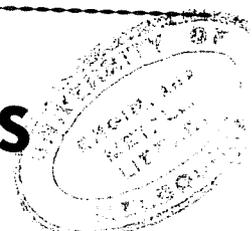
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Number 5

ULTRA LINEAR AMPLIFIERS

First article of a series by F. LANGFORD-SMITH

and A. R. CHESTERMAN



This first article gives a general introduction to the subject, with its history, some of its characteristics, and then an investigation into the effects of the tapping point on the power output and distortion. The effects of high resistive loads are also investigated.

1. Name

The name has been the subject of much controversy. "Tapped Transformer" and "Triode Tetrode" operation have been suggested in England, while "Partial Triode Operation" has been used in the Radiotron Designer's Handbook (Ref. 1). None of these seem to have taken on, so that we are left with the title "Ultra Linear", which will be used throughout this article in its abbreviated form, UL.

2. History

A claim has been made that the circuit was originated jointly by R. Lackey and R. R. Chilton of the Australian Radio College and distributed to students in the form of notes in 1933. Unfortunately, the early records were destroyed by fire, and no written description has been seen by the authors. If any one of our readers can produce the relevant documents, we would be happy to publish the fact.

The UL circuit (not, of course, under this name) was patented by the late A. D. Blumlein in 1937 (Ref. 2). It did not receive much publicity until 1951, when D. Hafler and H. I. Keroes (Ref. 3) published a fairly detailed description under their newly-coined appellation "Ultra Linear". Since then, it has attracted a good deal of attention and is now being widely used in place of pentode operation in high fidelity and other good quality amplifiers. Some of the many references are given at the end of this article. However, no satisfactory treatise on the subject has yet appeared with information

sufficiently detailed to satisfy an amplifier designer. The present article is the first of a series to meet this need.

3. Description

A typical circuit diagram is shown in Fig. 1. It differs from pentode operation by the screens being connected to tapping points T, T, on the transformer primary. It is always advisable to fit screen suppressors R3 and R4 and usually also condensers C1 and C2 between the plates and the transformer end of the screen suppressors, to eliminate a form of instability. Typical values are 0.001 or 0.002 μ F and 47 to 220 ohms. Grid stopper resistors (10K) are also desirable.

In this article, "pentode operation" is to be taken as including beam tetrode operation.

UL operation is a step between pentode and triode operation. When the tapping points are moved down to the B+ terminal, the valves operate as pentodes. When the two tapping points are moved to the plate ends of the windings, the valves operate as triodes; when the tapping points are in between, the operation is intermediate between triode and pentode operation. Any desired tapping points may be used—those closest to the B+ end give characteristics closely resembling pentodes and then as the tapping points are moved towards the plate ends the characteristics become more and more like triodes, until the extreme case is reached where full triode operation is obtained. **It is usual to refer to the tapping point as so many per cent. of the total impedance, and this practice will be followed in the present series of articles.** However, sometimes a tapping point is referred to as a percentage of the total number of turns. One may be converted to the other by using the relationship.

$$\text{Percentage turns} = 10\sqrt{\text{percentage impedance}} \quad (1)$$

For convenience, Table 1 has been calculated.

Table 1 — Tapping Point (from B+ end)

Percentage impedance	Percentage turns
0%	0% (pentode)
5%	22.4%
10%	31.6%
15%	38.7%
18.5%	43%
20%	44.7%
25%	50%
35%	59.2%
50%	70.7%
75%	86.6%
100%	100% (triode)

A complication with UL operation is that the screen voltage swings around the applied voltage. For example, with 250 volts applied, and a transformer tap of 20% impedance, the alternating screen voltage will be 44.7% of the alternating plate voltage (Table 1). If the plate load resistance is 5000 ohms (single-ended) and the power output is 5 watts, the r.m.s. plate voltage will be about 158 volts and the r.m.s. screen voltage will be about 70 volts.

The two most important effects of UL operation are on power output and total harmonic distortion. The power output with UL operation is always less than that with pentode operation and greater than that with triode operation, for constant applied voltages. As will be shown later, the maximum signal cathode current with UL is less than with pentode operation, and the cathode current efficiency is approximately the same, so that if the plate voltage is increased to give the same input power for both cases, then the output power will be the same for both UL-and pentode.

4. Optimum bias and load resistance

Up to now all experimenters seem to have assumed that the load resistance and bias for UL would be the same as for pentode operation. A graphical approach indicated that the optimum load resistance would be different, so tests were carried out on type KT66 as a typical example.

5. Type KT66, 300 volt operation

Many measurements were made on type KT66 with 300 volt plate and screen supply, and those are summarised in Fig. 2. Curve 1, marked "Max. power output", shows power output against percentage tap, and each point is the condition of bias and load resistance giving maximum power output irrespective of distortion. Curve 2 shows the power output when the bias and load resistance are selected for minimum total harmonic distortion. On both these curves the load resistance and grid bias for each point are marked on the curves. Curves 3 and 4 give the THD for each of the two upper curves. It will be seen that the difference in power output between curves 1 and 2 is fairly small (less than 0.5 db) and in most cases it is only necessary to consider the minimum distortion curve (2). The following conclusions can be derived for type KT66, for constant plate and screen voltages.

(a) Lowest distortion occurs at about the 20% tap. It is deleterious to go beyond this point, on account of the reduction in power output and in-

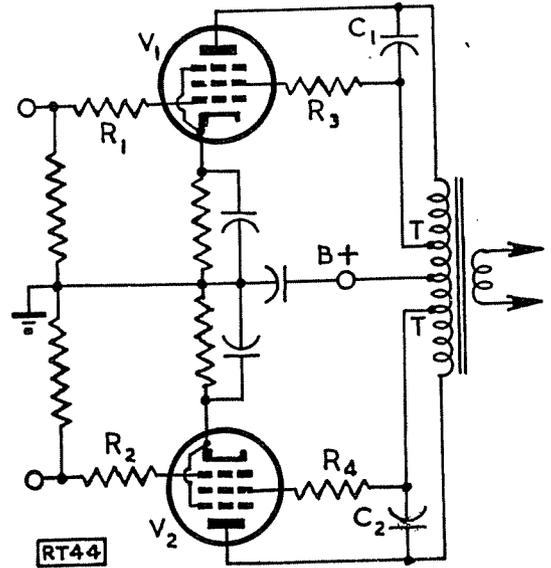


Fig. 1. Circuit diagram of a typical UL amplifier. (44.)

crease in distortion. At the 20% tap the power output is from 52% to 59% of the pentode maximum power, and the THD from 0.4% to 0.65%, depending on the bias and load resistance.

(b) The optimum tapping point for highest fidelity is between 17% and 20%, and it is not at all critical.

(c) The optimum tapping point for public address work is probably 5%. This gives from 73% to 78% of the pentode maximum power output, depending on the bias and load resistance, and from 0.5% to 2% THD. Of course, if the plate and screen voltages can be increased, it might be possible to use the 20% tap for P.A. with no loss of power output.

(d) Whether adjusted for minimum distortion or for maximum power, UL with 15% to 20% tapping points gives lower THD and higher power output than triode operation — see Fig. 2.

(e) The optimum bias for maximum power output is greater for UL than for pentode operation. It increases from —28 volts (pentode) to —30 and —34 volts (UL) and —34 volts (triode) — see Fig. 2. These values of maximum power output are irrespective of distortion and would not be used in practice for pentode operation, since by allowing a slight reduction in power output there would be a considerable reduction in distortion. However, the condition for maximum power output can be used for UL operation, since the distortion is low.

(f) The optimum bias for minimum THD decreases from —34V with pentode operation, to —26V with all UL tappings and for triode operation.

(g) The optimum load resistance for maximum power output is greater for UL than for either pentode or triode operation, increasing from 6K (pentode) to 6K, 7K, and 8K (UL), and back to 5K and 6K (triode) — see Fig. 2.

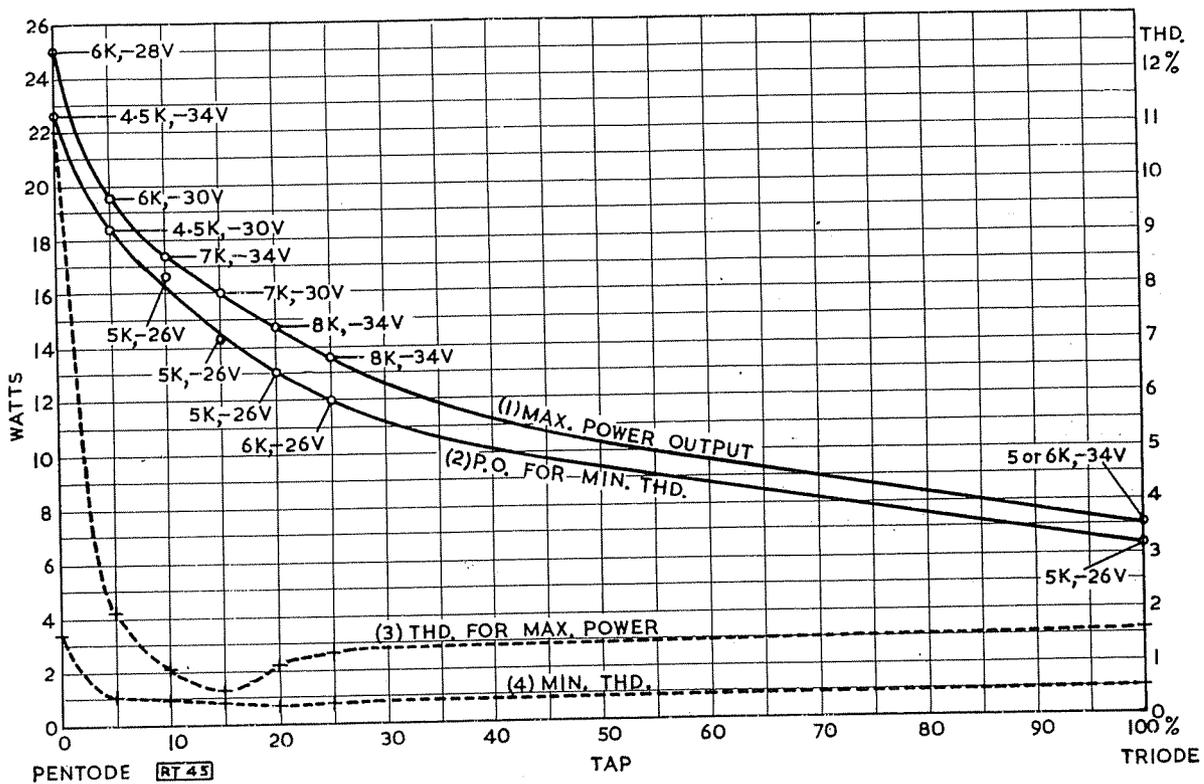


Fig. 2. Effect of tapping point on power output and total harmonic distortion. Type KT66's with $E_b = E_{c2} = 300$ V. Optimum bias and load resistance for each point. (RT45.)

(h) The optimum load resistance for minimum THD increases from 4.5K (pentode) to 5K for UL 10% to 20%, up to 6K at 25% tapping, and down to 5K for triode operation — see Fig. 2.

The detailed test results on which the curves of Fig. 2 were based are shown in Fig. 3. The effect of load resistance on power output is quite small over the range shown, but its effect on distortion is very marked. The effect of bias voltage is also more marked on distortion than on power output. Note that the minimum distortion point for pentode operation is quite critical, both on bias voltage and load resistance (although not shown in Fig. 3), whereas the 20% UL tapping gives almost constant distortion over the range of load resistances shown, for any bias voltage between -26 and -30 volts. This is a very valuable feature.

Note the surprising low distortion possible with pentode operation and a load of 4500 ohms—1.7% THD at -34 volt bias, but the operating point is rather critical.

The readings for distortion are only relative owing to the difficulties in reading a THD meter at very low levels, and the distortion in the signal voltage applied to the grids (up to 0.2%). There is necessarily some cancellation and accentuation of harmonics due to harmonic phase relationships between the input source and those produced in the amplifier. The Appendix gives the detailed conditions of testing.

6. Screen dissipation

The static screen dissipation will normally be slightly less than that for pentode operation, because of the increased bias. Since the screen makes some contribution to the total power output, the dynamic screen dissipation is not given by the screen input power. The maximum signal screen dissipation for identical operating conditions in each case, is highest for pentode operation, lowest for triode and UL is intermediate between the two. For this reason pentodes may sometimes be used with UL operation under conditions when pentode operation would cause the screen dissipation rating to be exceeded. The screen power relationships may be expressed:—

$$\text{Screen dissipation} = \text{screen input power} - \text{power output} \dots\dots\dots (2)$$

It is usually not convenient to measure the screen power output and, so long as the maximum signal screen input power is below the screen dissipation rating, the valve will be operating well within its ratings.

Fig. 4 shows the screen current plotted against tapping point for 300 volts and -30 volt bias. The lowest curve shows the zero signal current per valve, while the two upper curves show the maximum signal screen current for 5K and 8K load resistances. It will be seen that the 5% tap reduces the screen current to 57% and 55% respectively of the pentode value. Fig. 4 applies to a pair of typical valves, but wide tolerances occur in the screen currents drawn by all beam tetrode valves.

7. Plate current

Table 2 gives values of plate currents per valve, obtained by subtracting measured screen currents from cathode currents, at 300 volts and -28 volts bias.

Table 2

Plate current			
Max Signal			
Operation	Zero Sig.	Load 5K	Load 8K
Pentode	49.1	71.5	59.75
10%	48.1	63.9	57.3
20%	47.75	61.0	56.5
Triode	44.5	50.9	48.7

The differences between the zero signal plate currents are due to the resistance in the output inductor.

Table 2 shows that with UL operation the plate current rise with maximum signal is less than that with pentode operation for the same operating conditions, but the power output is less, so that no conclusion can be drawn. Table 3 (below) gives similar data in respect of the cathode current.

8. Linearity

Linearity curves are given in Fig. 5, where A is for pentode operation, and B, C, and D various UL conditions. The THD at the grids was reduced to 0.13% for Fig. 5 only. The linearity characteristics were measured using peak reading valve voltmeters for both grid and plate voltages, in order to get a true result*. The disadvantage of this procedure is that the power output indicated by the valve voltmeter is appreciably less than the actual power output when the THD exceeds about 1%. As a consequence, it has not been practicable to add the power output readings to the pentode linearity curve. The approximate power output may be calculated by multiplying the power indicated on the curve by a factor of 1.1 for 5% THD.

The pentode curves for maximum power output are given in Fig. 5A. Note the "shelf" in the distortion curve from about 15 to 19 watts output. The linearity curve deviates from the straight line about 2 watts power output, and the slope of the curve at maximum power output (input voltage 17.5 volts) is only 34% of that at low levels. This reduces the effective feedback at maximum power output.

The UL 5% curve is given in Fig. 5B. This is practically linear up to 2.5 watts and the deviation is distinctly less than for the pentode, although its shape is rather unusual. The THD curve reaches a maximum of 1% between 9 and 13 watts, then comes down to about 0.8% (minimum) at 18 watts before rising to 1.4% at zero grid.† Although this form of distortion characteristic is generally undesirable, the THD at any level is much below that for pentode operation. In the distortion

† The zero grid line is where the peak input voltage is equal to the bias.

* An article on linearity characteristics will appear in a future issue.

curves of Fig. 5 there is undoubtedly some effect from in-phase and out-of-phase relationships between the harmonics in the signal source and the UL stage, so that the exact shape of the distortion characteristic is uncertain, having a maximum possible tolerance of ± 0.26 in the reading of the total harmonic percentage at any point (i.e. twice the distortion in the source).

The UL 10% curve is given in Fig. 5C and has the same general characteristic as for the 5% curve, but better linearity. It is practically linear up to 4 watts. The measured THD reaches a maximum of 0.77% between 8 and 14 watts, falling to 0.68% (minimum) at 17.5 watts and rising to 1% when the peak grid voltage reaches zero. In practice, with a high impedance source, it would not be possible to drive the grid to zero voltage without introducing distortion into the driver voltage.

The UL 20% curve is given in Fig. 5D and is practically linear within the limit of accuracy of the measurement up to 15 watts. The voltage gain is constant at 7.15 times right up to 15 watts. The measured THD shows a steady rise up to 0.6% at 15 watts, being about one-tenth of that for pentode operation. The whole performance is quite remarkable.

9. Efficiency

The cathode current efficiency for pentode operation was measured under the conditions giving maximum power output. Three different conditions for UL operation were also measured, and are given in Table 3.

The pentode and the first UL condition given above are the respective conditions for maximum power output given in Fig. 2. The second UL condition is for the bias and load resistance which give maximum power output with pentode operation; it is therefore not optimum for power output or efficiency with UL operation. The third UL condition is intermediate between the other two UL conditions; it also is not optimum for power output or efficiency with UL operation.

Table 3 shows that, by selecting the UL condition giving maximum power output, the efficiency is 49.8% compared with 51.2% for the pentode. This is quite a remarkable performance, especially since the pentode output includes about 11% distortion, with the large third harmonic component giving an effective increase in the power output for a limited swing (Ref. 12). On the other hand the UL output had only about 1% total harmonic distortion, with a negligible effect on the power output.

Under the conditions for maximum power output in both cases, the efficiency with the 10% tap was slightly higher than for the 20% tap.

Thus UL operation, using conditions for maximum power output, will give nearly the same power output from a specified d.c. power input as will pentode operation. It merely requires somewhat higher plate voltage and somewhat less plate current than for pentode operation.

In addition, a specified valve, operating with constant d.c. input power, will give nearly the same power output with UL operation as it will with

pentode operation (each being operated under its own optimum conditions), and the total plate plus screen dissipation will be about the same. Hence, since the screen dissipation with UL is less than

with pentode operation, the plate dissipation will be greater by the amount that the screen dissipation was reduced—in most cases this is only a very slight amount.

Table 3
Type KT66, Supply Voltage, 300 Volts

Condition	I _k (mA)	Power input	Power output	Efficiency		
					no sig.	max. sig.
Pentode	6K, —28V	105	165	48.8W	25W	51.2%
UL 20%	(1) 8K, —34V	60	99	29.6	14.8	49.8
	(2) 6K, —28V	108	122	36.4	14	38.5
	(3) 7K, —30V	88	116	34.5	14.2	41

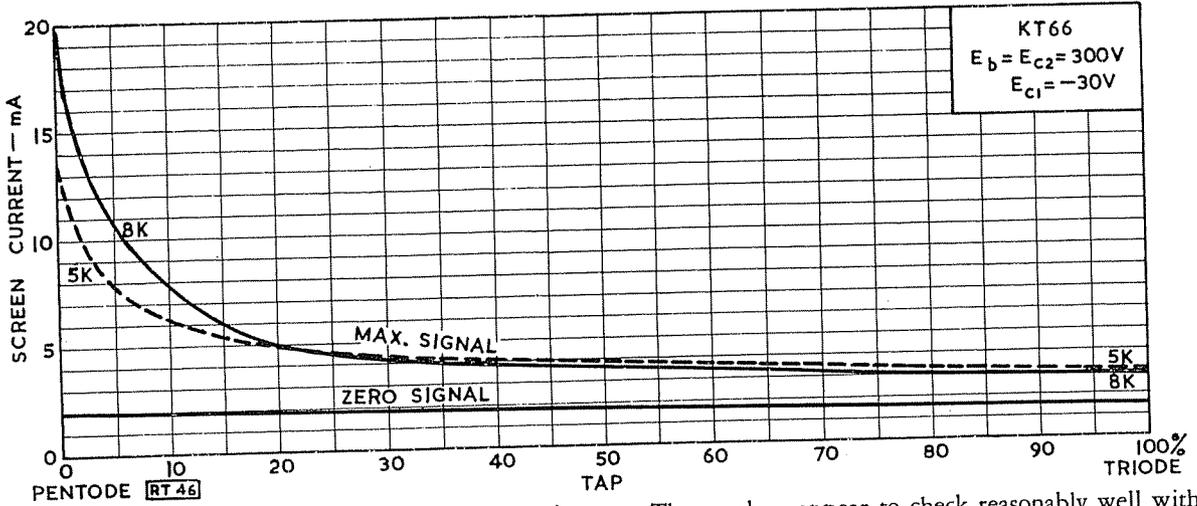


Fig. 4. Effect of tapping point on maximum signal screen current for a single valve, for load resistances of 8000 and 5000 ohms, and E_b = E_{c2} = 300 V. Zero signal screen current is also given. (RT46.)

10. Negative feedback

The UL amplifier has internal negative voltage feedback which decreases the total harmonic distortion and reduces the output resistance and the gain, when compared with pentode operation. Each of these characteristics is intermediate between the values for triode and pentode operation.

However, the feedback cannot be treated as pure feedback, because it reduces the maximum power output and requires additional bias and higher load resistance for optimum operation.

The non-linearity known to exist in the screen characteristic is not the cause of these two phenomenon, which are fundamental, although it must have some effect on non-linear distortion. A further point in support of our conclusion is that the distortion with UL is not intermediate between pentode and triode, but is lower than either.

Measured values of the voltage gain are given below for KT66, E_{bb} = E_{c2} = 300 V, E_{c1} = -30 V and R_L = 6000 ohms.

Operation	Gain	Ratio
Pentode	10.2	1
5% tap	9.15	0.9
10% tap	8.6	0.84
20% tap	7.7	0.75

These values appear to check reasonably well with the gain reduction ratio derived from Williamson and Walker (Ref. 5) on the assumption that this can be treated as pure voltage feedback.

$$\text{Ratio} = \frac{1}{1 + \frac{X}{\mu_t} \frac{\mu R_L}{r_p + R_L}} \dots \dots \dots (3)$$

- where ratio = 1 for pentode operation
- X = fraction of output voltage fed back to screen
- = percentage turns of tapping point ÷ 100
- μ = pentode mu
- μ_t = triode mu (screen connected to plate)
- r_p = plate resistance of valve
- and R_L = load resistance for single valve
- = ¼ × load resistance plate-to-plate.

11. Overload characteristics and distortion

The overload characteristics as observed on an oscilloscope differ fundamentally from those of pentodes, although they bear some resemblance to those of pentodes with a high degree of feedback. Pentodes show slight flattening of the peak some distance before reaching maximum power output, the minimum visible being about 3 or 4%. UL amplifiers without feedback show no visible deformation until

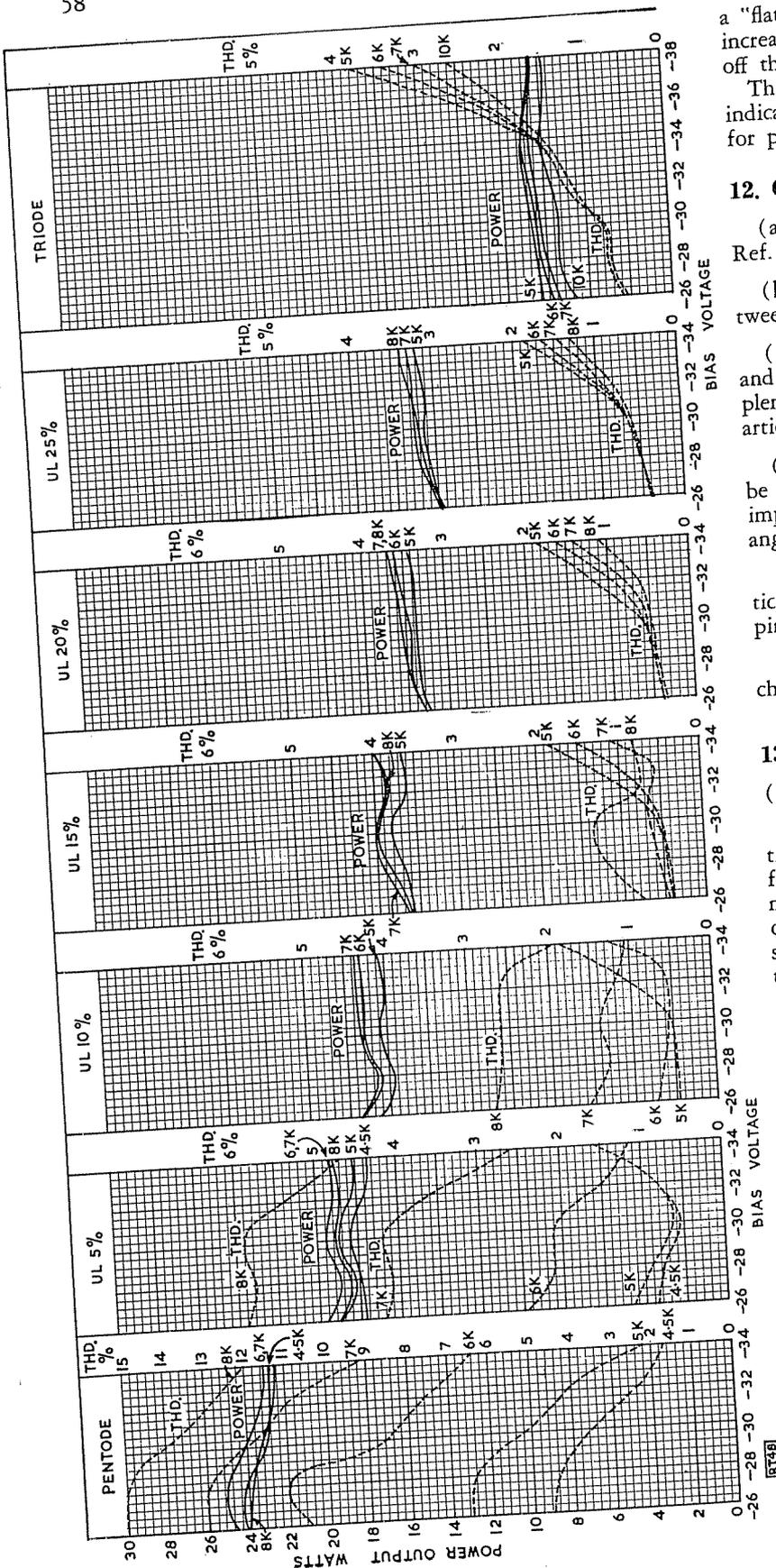


Fig. 3. Power output and total harmonic distortion versus grid bias voltage, for selected values of grid bias resistance. (RT48.)

a "flat" appears at about 0.6%, and as the drive is increased this extends in a straight line chopping off the whole top of the peak.

This method is very much more sensitive as an indication of total harmonic distortion for UL than for pentode operation.

12. Characteristics deferred for a later article

- (a) Input impedance (Miller Effect), see also Ref. 11.
- (b) Output resistance. This is intermediate between pentode and triode operation.
- (c) Non-linear distortion. Tests of IM distortion and measurement of individual harmonics to supplement total harmonic distortion as used in the article.
- (d) The effects of a loudspeaker load. This may be simulated by a dummy load having a high impedance and a choice between 45° and zero phase angle, in addition to the normal purely resistive load.
- (e) Effect of tolerances in the valve characteristics, especially screen current, on the optimum tuning point and other performance characteristics.
- (f) Graphical examination of the composite characteristics with loadlines.

13. General comments

(a) Comparison with pentode operation. The principal advantage of UL is that the distortion is so very much lower that the total circuit feedback can be less, leading to a higher stability margin or in many cases making possible the use of a cheaper output transformer for the same stability margin. Another important advantage is that the linearity characteristic for the 20% UL is practically straight up to the grid current giving constant amplifier gain even without feedback. In this respect it appears to be as good as triode operation, and results in the full amount of feedback being applied at all levels. Pentodes suffer from drooping linearity characteristics and only about one-third of the full amount of feedback is applied at high levels where it is most wanted.

When compared on the basis of power output on a constant supply voltage (e.g. Fig. 2) UL operation shows a serious drop in maximum power. This drop in power output occurs because, at the positive peak of the grid driving cycle, the grid voltage is reduced below that which would be obtained with the pentode operation, so that the m

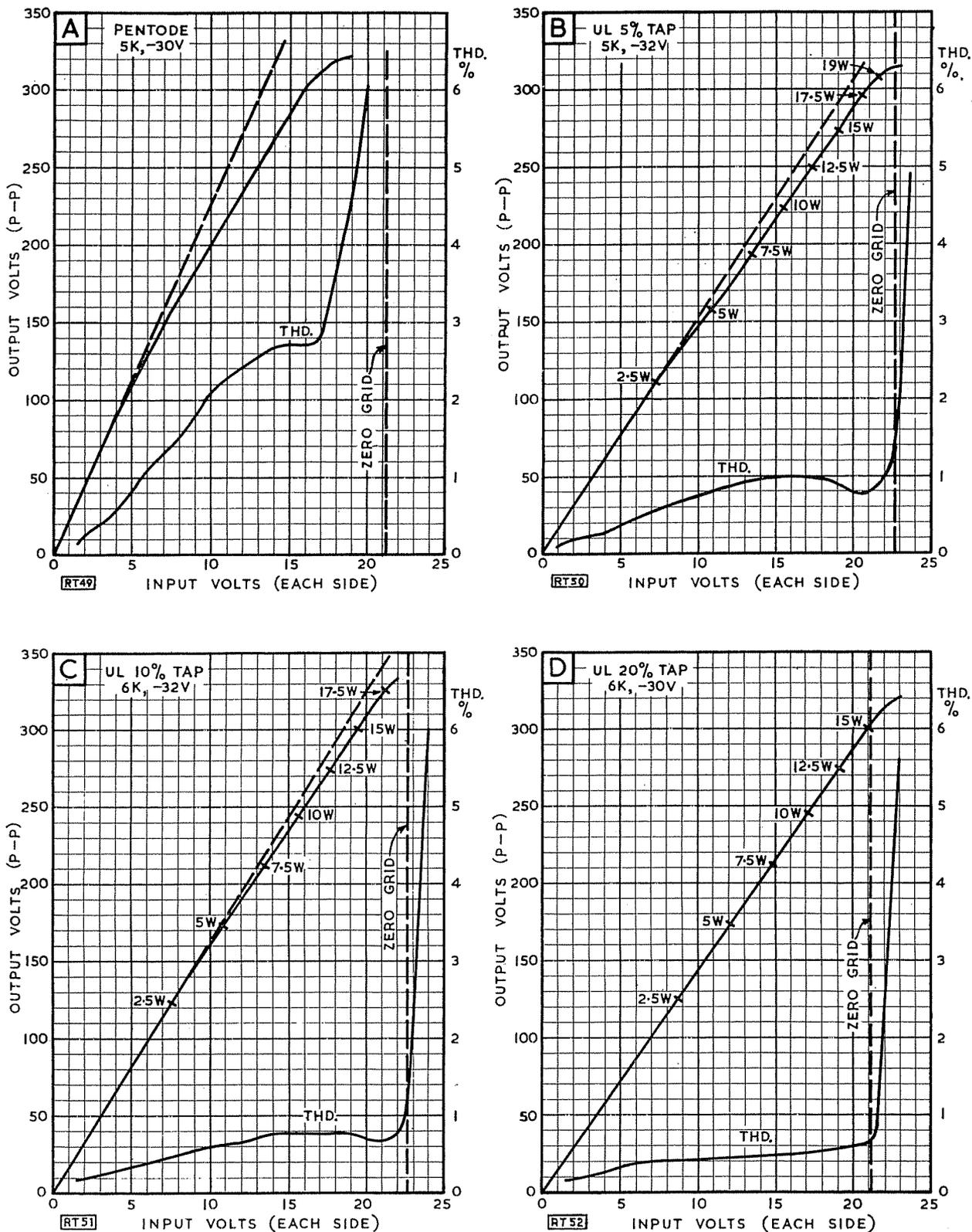


Fig. 5. Linearity curves, with total harmonic distortion, for KT66 with $E_b = E_{c2} = 300$ V:
A. Pentode $E_{c1} = -28$ V, $R_L = 5000$ ohms (RT49).

B. UL 5%, $E_{c1} = -30$ V, $R_L = 5000$ ohms (RT50).
C. UL 10%, $E_{c1} = -30$ V, $R_L = 6000$ ohms (RT51).
D. UL 20%, $E_{c1} = -28$ V, $R_L = 6000$ ohms (RT52).

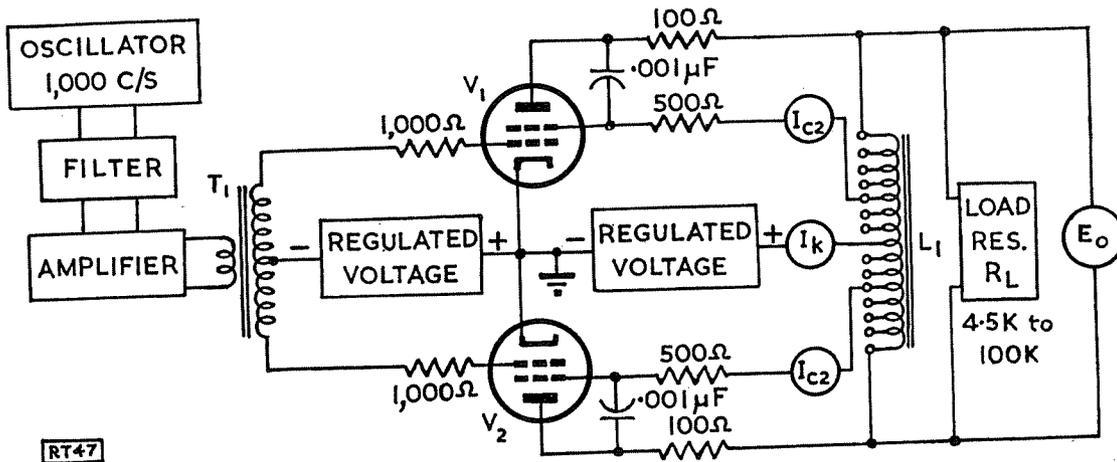


Fig. 6. Circuit used for deriving test results published in this article. (RT47.) Note that the $0.001 \mu\text{F}$ condensers are in different positions to those shown in Fig. 1.

signal plate current is reduced. However, the efficiency may be made to be almost the same as for pentode operation, and, circumstances and valve voltage ratings permitting, if the UL amplifier is supplied with the same power input as the pentode, by increasing the UL supply voltage, approximately the same power output will be given by both and the combined plate and screen dissipation will be roughly the same.

UL operation not only reduces the distortion, but it makes the load resistance less critical over the limited range used in these tests. It is hoped to investigate this matter more fully at a later date.

The screen dissipation is less with UL operation, so that conditions of operation are sometimes permissible with UL which are not permissible with pentode operation. The only disadvantages of UL compared with pentode operation appear to be the slight loss in voltage gain, the reduced power output (unless the supply voltage is increased) and the slightly increased cost due to the tapped transformer and the stopper condensers (although the latter are sometimes used with pentodes).

(b) Comparison with triode operation.

UL operation has higher power output, greater efficiency, less total harmonic distortion and requires less driving voltage. When overloaded, it suffers from a particularly flat form of flat top even without any external feedback.

Operation on a loudspeaker load has not been covered by the present series of tests, but it is hoped to publish further results in the near future. However, a graphical check has been made on the only valve type for which UL characteristics were readily available (type 5881), leading to the conclusion that high load resistance will cause high distortion. If this is substantiated in later measurements, it leaves the triode output stage still as the ideal when its performance on a loudspeaker load (and not a fixed resistive load) is considered. However, this must be at the expense of larger power supply, and larger input voltage.

(c) Operation.

The point for minimum distortion is given, at least for type KT66, by a tapping point from 17% to 20% impedance, and the optimum grid bias and load resistance will both be greater than for pentode operation on the same supply voltage. Comments on increasing the screen voltage have been made in (a) above.

When used as a public address amplifier with the 5% tap, the loss in power output is only about 20%, and yet there is an outstanding reduction in non-linearity when compared with pentodes.

14. Appendix

14.1. Test conditions

The test circuit used for these measurements is shown in Fig. 6. The oscillator harmonics were reduced by a filter, and the amplifier non-linear distortion was reduced by the use of a large amount of feedback, so that the total harmonic distortion at each grid did not exceed 0.2% (0.13% for the linearity curves). The input transformer T_1 was made with a C core and an inductance of 100H, with a set-up ratio of 1:2 primary to whole of secondary. The leakage inductance was 16mH primary to whole of secondary, and 36mH primary to half secondary.

A tapped inductor I_1 was used in preference to a transformer, tapped at 5, 10, 15, 20, 25, 35, 50 and 75% of the impedance on each side. Its inductance plate-to-plate was 350H at low level, 500H at 240V 50 c/s, with leakage inductance from one half-winding to the other half 10mH. The d.c. resistance was 440 ohms total.

The large number of taps and switching facilities gave a tendency towards instability, which was avoided by the use of grid, screen and plate stoppers, and by capacitors of $0.001 \mu\text{F}$ between plates and screens.

The input voltage was measured separately on each side of the secondary T_1 , using a valve voltmeter, but the values were almost identical. An oscilloscope was connected in turn from each grid to earth and the side showing earliest signs of "flattening" was used as an indicator. The input

was decreased until there was no visible deformation of a greatly enlarged waveform peak.

The output voltage, which was used for deriving the power output was measured with an Avo Model 8 rectifier type meter. This is the type of instrument commonly used in power output meters. This was checked for accuracy against a Western dynamometer type voltmeter. For pentode operation the error was between +2% and +3.5% from 100 to 240 volts, falling to zero from 270 to 300 volts. For UL operation the error was about +2% from 100 to 230 volts, zero at 250 volts, -1% at 270 volts, and zero again at 300 volts.

Before measuring distortion, the input and output voltmeters and the oscilloscope were disconnected, since they had an appreciable effect on the distortion.

The linearity tests were carried out with r.m.s. calibrated peak-reading valve voltmeters in both input and output circuits.

The supply voltage for the present series of tests was approximately 304 volts, giving very close to 300 volts between positive electrodes and cathodes.

15. References

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"ULTRA LINEAR" AMPLIFIERS

by F. Langford-Smith and A. R. Chesterman.

This article treats 6V6-GT operation and makes a comparison between UL operation and the divided plate and cathode loading method used in the QUAD II and other amplifiers.

1. Type 6V6-GT UL operation.

Fig. 1A shows the power output versus tapping point for plate and screen 285 volts, and bias -19 volts, for selected values of load resistance. Fig. 1B shows the total harmonic distortion.

Figs. 2 and 3 show the same information for bias values of -21 and -22.5 volts. From these it appears that the 5% tap is the best all-round compromise, giving minimum distortion for -21 volts bias and 8000 ohms load resistance.

Fig. 4 shows the power output and distortion against grid bias. These confirm the impression

given by the other figures, indicating a bias of -21 volts as optimum for power output and giving reasonably low distortion.

The load resistance of 8000 ohms plate-to-plate was selected as optimum, giving an output of 10.4 watts at 0.72% THD, even though an output of 11.2 watts was obtainable with a load resistance of 10,000 ohms. The reason for the choice is partly to make it less sensitive to increases in load resistance such as always occurs with a loudspeaker load, and partly to make the transformer simpler and with fewer primary turns.

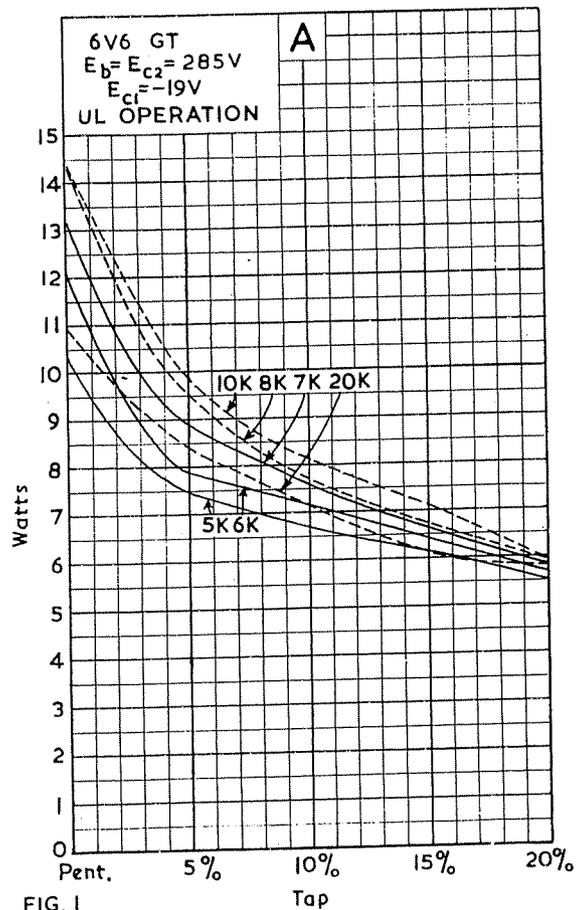
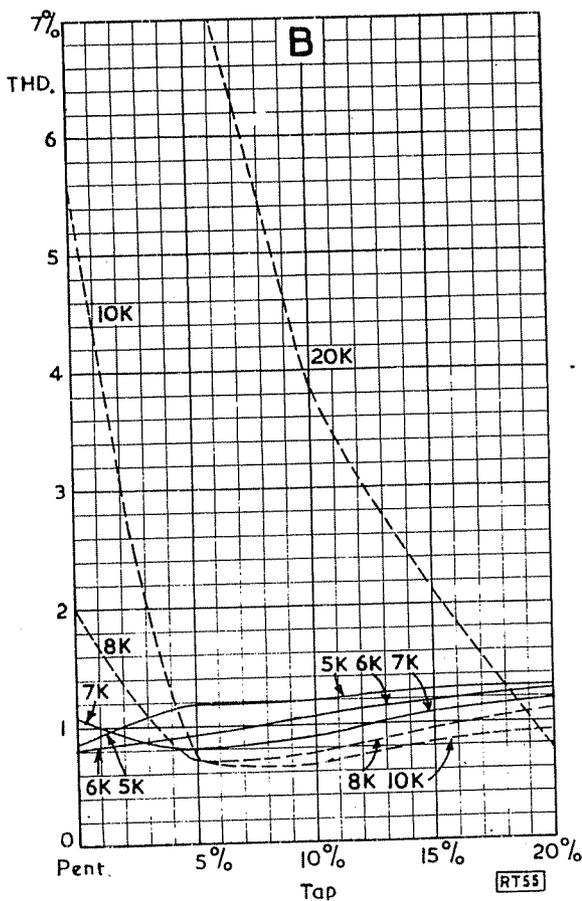


FIG. 1

Fig. 1. 6V6-GT push-pull UL operation, $E_b = E_{c2} = 285V$, $E_{c1} = -19V$, peak grid voltage equals bias; (A) Power output versus tap; (B) Total harmonic distortion versus tap (RT54).

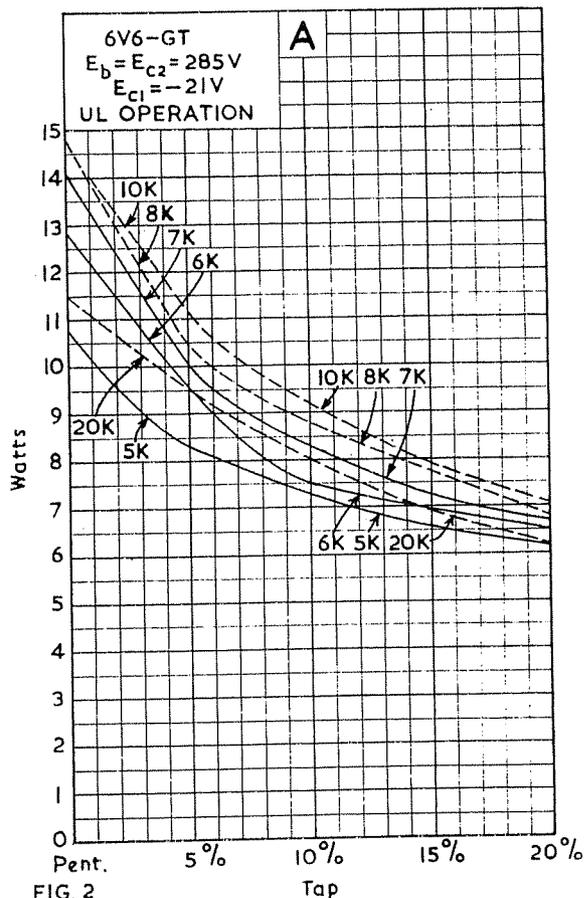
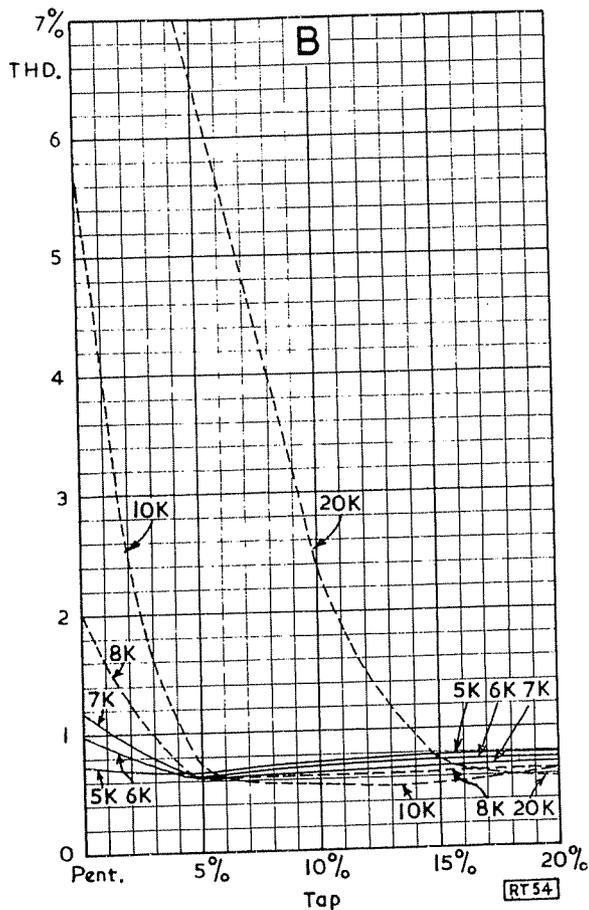


Fig. 2. 6V6-GT push-pull UL operation, $E_b = E_{c2} = 285V$, $E_{c1} = -21V$, peak grid voltage equals bias; (A) Power output versus tap; (B) Total harmonic distortion versus tap (RT55).

If high power output had been unimportant, a tapping point of 15% or 20% might have been selected to make the load resistance less critical for distortion. However, this distortion is less than that with pentode operation. The whole question of distortion with high impedance loads, such as occur with loudspeakers, will be treated in full detail in a later article in this series, and comparisons made between UL, triode and pentode operation.

The selected condition gives 71% of the output obtainable with the same valves as pentodes under

the same conditions except that the bias is the published value (-19 volts).

The curves and other data are for operation in the conventional way with the peak signal voltage equal to the bias ("zero grid"). Of course, in any practical amplifier, it is not possible to drive to zero grid without grid current and consequent distortion, and the consequent reduction in effective power output applies to all types of operation. The output resistance under these conditions without external feedback is 15,400 ohms plate-to-plate. With the 20% tapping, this figure would become 9,600 ohms.

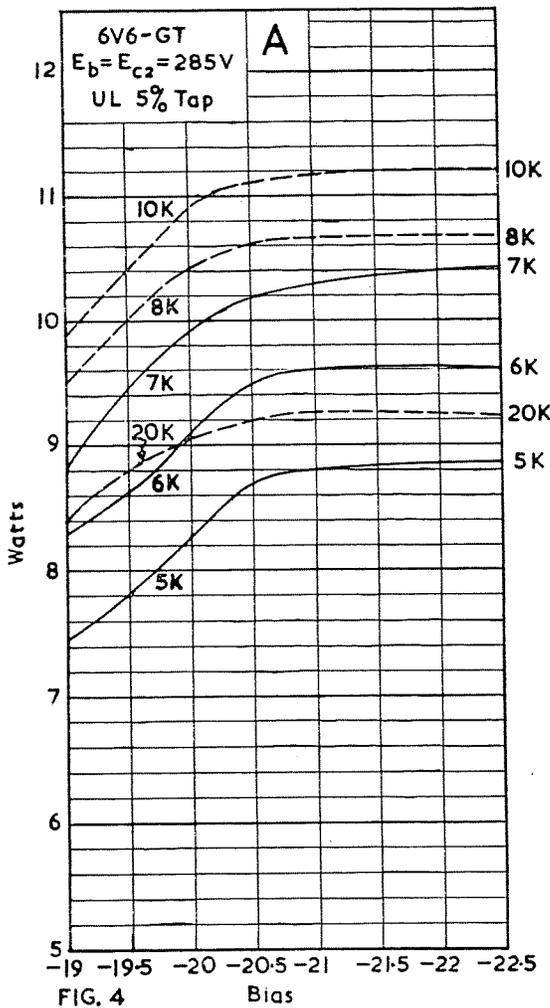


FIG. 4

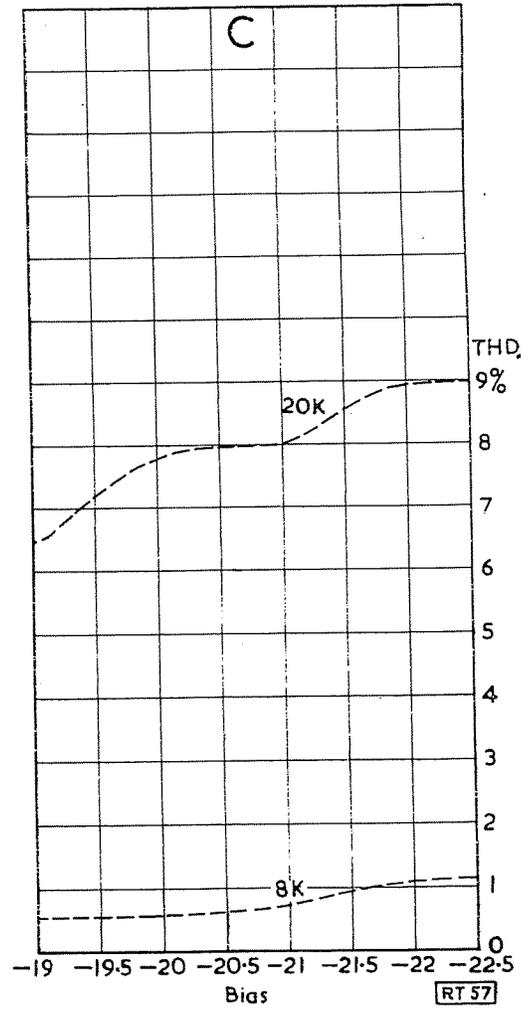
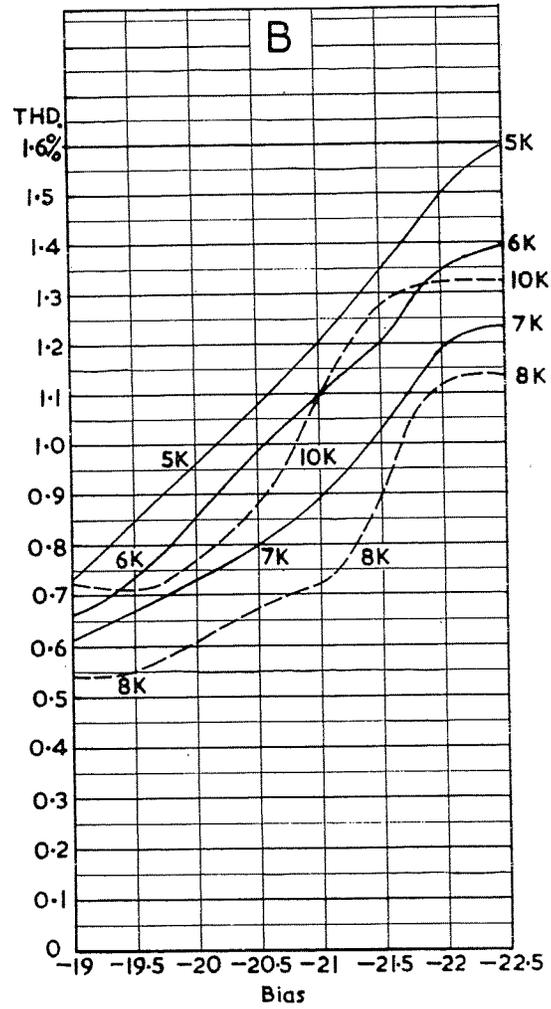


Fig. 4. 6V6-GT push-pull UL operation, $E_b = E_{c2} = 285V$, tap 5%, peak grid voltage equals bias; (A) Power output versus bias; (B) Total harmonic distortion versus bias; (C) Total harmonic distortion versus bias for 20,000 ohm load, with 8,000 ohm load for comparison. Note that THD scales in B and C differ (RT57).

2. Comparison between UL and divided plate and cathode loading.

Divided plate and cathode loading is used in the QUAD II and other amplifiers (Ref. 1 and 2). The transformer half-primary is in two sections, part connected from cathode to earth and part from plate to B+, while the screen is bypassed to earth. It is obvious that there will be an a.c. voltage between screens and cathodes in the same way as the UL amplifier—in fact, it can be kept to the same value if desired. Thus divided loading operation has a performance in some ways similar to that of the UL operation. The principal difference is that divided loading has additional negative voltage feedback in the cathode-grid circuit.

For equivalent results with divided loading the cathode winding should have the same proportion of the total impedance as for UL operation. For example, with type KT66 this impedance ratio should be about 20%. In effect, the transformers will differ only in that the winding for the former is broken at the tapping point.

The choice between UL and divided loading will be influenced by the reduced gain with the latter. In most other respects the two methods are quite similar, and results for one apply very closely to the other.

The measured impedance ratio in the QUAD II amplifier is 3.5%, which is considerably less than the optimum (20%) found in our tests of type KT66. It seems likely that the preceding stage gain is insufficient to permit optimum operation of the output stage, but this will be checked later by direct measurement.

It is hoped to publish, at some future date, test results using a special output transformer permitting divided loads with a choice of several impedance ratios.

† Radiotronics, May, 1955.

3. Comments on UL operation.

The UL amplifier is quite distinctive, neither a pentode nor a triode, but with its own marked characteristics. Its power output is definitely less than that of a pentode, as is clearly shown for type KT66 by Fig. 2 of Part 1 of this series†. This effect has often been obscured by the choice of conditions to give optimum performance for UL operation and then, without any other change except the connection of the screens on the transformer, measuring the power output for pentode operation. As shown in the earlier article, this would not give optimum pentode operation, so that the comparison is not a fair one. This remark applies particularly to the curve published by Hafler and Keroes.

Secondly, the reduction in distortion with UL operation is much greater than the reduction in gain. Taking Figs. 5A and B from Part 1 of this article, which are both for 5000 ohm loads, the ratio of gains from pentode to UL 5% operation is approximately 1.48 times (from the slopes of the tangents to the linearity characteristics). On the other hand the ratio of total harmonic distortion varies from approximately 1.4 times at low levels, to over 3.3 times at 18 watts, for the same power output in both cases. The same effect holds under all conditions which we have measured, for type 6V6-GT as well as KT66.

Thirdly, the optimum load resistance for UL operation, in all cases so far tested by us, is greater than that for pentode operation.

Fourthly, the shape of the plate characteristics of the valve is distinctly different from those of either triodes or pentodes.

These points all indicate that UL operation is distinctly different from either triode or pentode operation, and should be regarded as a separate phenomenon.

References.

1. W. N. Williamson and P. J. Walker, "Amplifiers and Superlatives", W.W. 58.9 (Sept., 1952), 357.
2. P. J. Walker (letter), "Ultra-linear Operation", W.W. 60.12 (Dec., 1954), 593.

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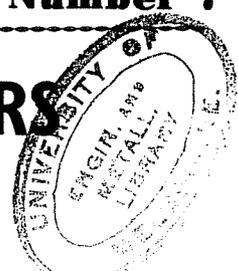
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ULTRA LINEAR AMPLIFIERS

PART 3

by F. Langford-Smith and A. R. Chesterman

This article gives the output resistance and screen power output.



1. Output resistance

Curves of measured output resistance for type KT66, plate-to-plate, with 300 volt supply are given in Fig. 1 for two extreme values of bias (Curves A and C). Curve B is the calculated curve, using the method outlined below, using the same bias as for curve A. Curves A and B agree, within the instrument errors, for tapings of 12% or higher, thus indicating that the calculation is valid.

The method used for measuring output resistance is given elsewhere in this issue.

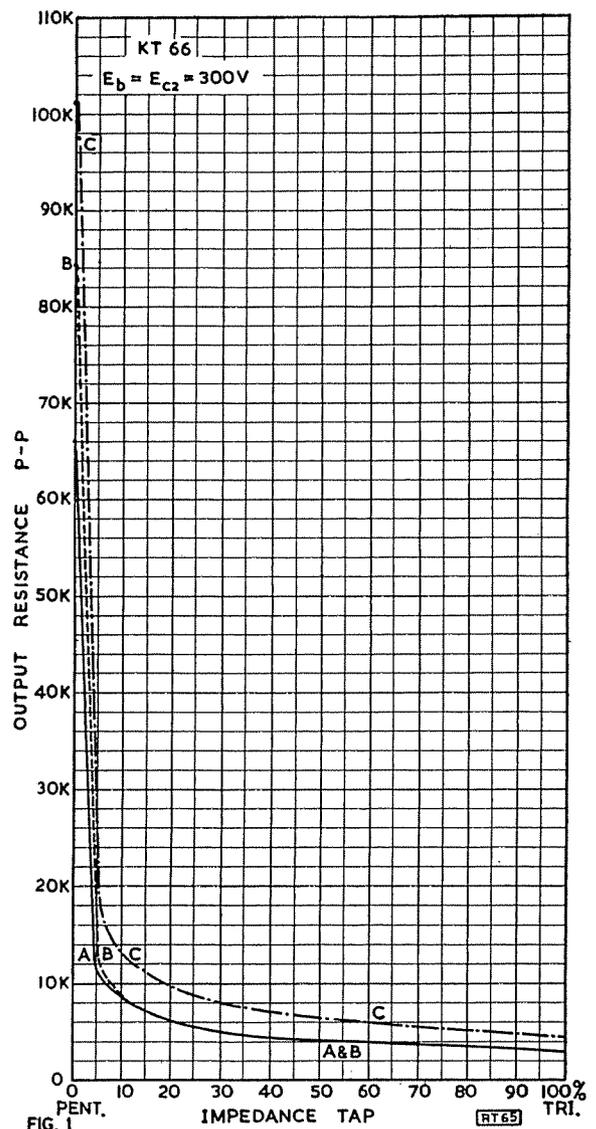
This measurement applies to the whole set-up, including the output transformer, plate and screen series resistors and 0.001 μ F condensers from plates to screens. In our particular case, since the multi-tapped inductor L_1 (Ref. 1) did not have a secondary winding, an A & R UL 20 watt output transformer was connected with its primary in parallel with L_1 , and some inaccuracy thereby introduced in readings for R_o above 10,000 ohms plate-to-plate. Since the 100 ohm plate stopper resistors are included in the measurement, the measured plate-to-plate resistance should be decreased by 200 ohms to give the valve output resistance.

The output resistance may be calculated, using the expression based on that derived by Williamson and Walker (Ref. 2.):

$$R_o = \frac{r_p}{1 + x\mu / \mu_t} \quad (1)$$

where R_o = plate resistance (per valve)
 μ = pentode mu at working point
 r_p = pentode r_p at working point
 x = percentage turns of tapping \div 100
 and μ_t = triode mu (screen connected to plate).

Fig. 1. Output resistance plate-to-plate versus tapping for type KT66, push-pull operation, supply voltage 300 V; (A) Measured at -26 V, $R_L = 5000$ ohms; (B) Calculated at -26 V; (C) Measured at -34 V, $R_L = 8000$ ohms (RT65).



The two valves used for the measured curves had the following average characteristics at $E_b = E_{c2} = 300$ V, $E_{c1} = -26$ V:

$\mu = 227$; $r_p = 44,300$; $\mu_t = 7.7$; $\mu/\mu_t = 29.5$.

The calculations are tabulated below:

Impedance ratio	x	Output resistance	
		per valve	plate-plate
0%	0	44,300	88,600
5%	0.224	6,830	13,760
10%	0.316	4,300	8,600
15%	0.387	3,580	7,160
20%	0.447	3,120	6,240
100%	1.0	1,450*	2,900

* This checks well with the direct measurement (triode) 1500 ohms

References

1. Part 1 of this series, Radiotronics, May 1955, p. 60, Fig. 6.
2. Williamson & Walker "Amplifiers and Superlatives", W.W. 58.9 (Sept., 1952), 357.

2. Screen power output

With UL operation the screen contributes a percentage of the total power output. The screen power output may be determined for a single valve from the expression:—

$$\text{P.O. (screen)} = \text{screen a.c. voltage} \times \text{screen a.c. current}$$

where all these values refer to those measured on a single valve. The screen a.c. voltage may either be measured directly or calculated from the plate a.c. voltage and the turns ratio of the transformer. Before the screen a.c. current can be measured, it must be separated from the screen d.c. current by means of a choke-capacitor network.

The total power for a pair of push-pull valves is twice that for a single valve. The fact that the screen was delivering power and not receiving power was checked by noting that the screen a.c. voltage at the screen itself was greater than that on the supply side of a series resistor.

Measured results are shown in the curves of Fig. 2, for type KT66 under stated conditions. Curve A shows that the percentage of total power contributed by the screen varies from 2.3% at the 5% tap, steadily increasing to 7.8% for triode operation. Curve B shows that the total power contributed by the screen under the selected conditions increased from less than 4% with a 5000 ohm load to 5.85% with a 10,000 ohm load.

The impedance (R_s) into which a single screen works was calculated from the known screen power output.

Let I_s = screen a.c. current per plate

and E_s = screen a.c. voltage per plate.

Then P.O. (screen) = $E_s I_s = I_s^2 R_s$.

Therefore $R_s = E_s / I_s$.

For example, with type KT66, 300 volts, $R_L = 5000$ ohms plate-to-plate, 13 watts, 20% tap: $E_s = 57$ V per valve

Measured $I_s = 45$ mA per valve

Screen power output per valve = $E_s I_s = 0.256$ W

$R_s = E_s / I_s = 12,700$ ohms per valve.

Also screen power output per valve = $(I_s)^2 R_s = 0.256$ W, agreeing with the result obtained by the other method.

Note that this calculated value of R_s , the impedance into which a single screen works, is considerably greater than the proportion of the load resistance R_L , which is reflected through the transformer to the tapping point. This result is to be expected from fundamental network analysis, in which two generators feed a common load resistance in phase; each generator "sees" a higher load resistance than the actual load. For those who are interested, a simple analysis along these lines will appear in a future issue.

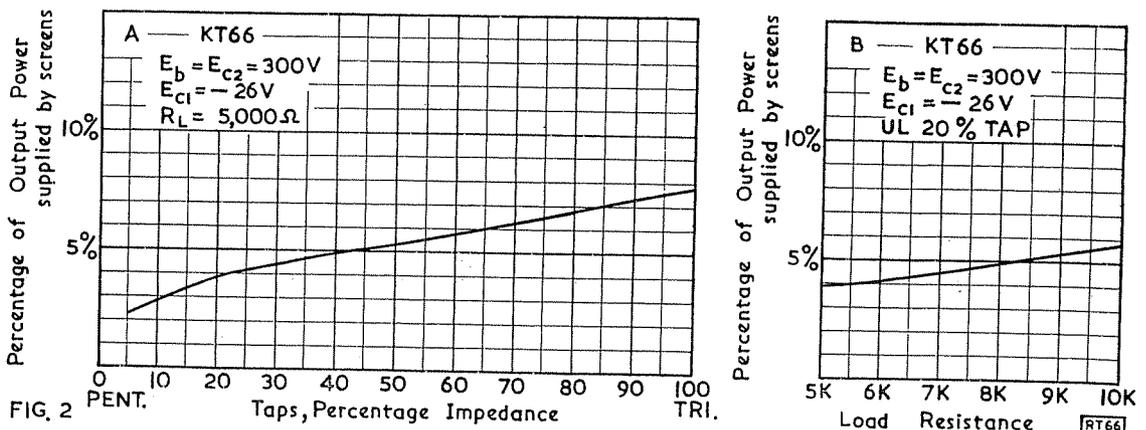


Fig. 2. Percentage of output power supplied by the screen, for type KT66; (A) versus tapping point; (B) versus load resistance (KT66).