A Transformer for a Single-valve Output Stage

USING AN OLD COMPONENT AND SIMPLE FORMULÆ TO OBTAIN THE DESIRED PERFORMANCE

By N. P. Fish

THERE is a widespread idea that satisfying reproduction in the home cannot be obtained without a 10-watt amplifier employing a push-pull output stage. An actual listening comparison between such equipment and a conventional " domestic " receiver with single pentode output valve usually argues convincingly in favour of the larger output. Yet, of an available 10 watts, how many are called for in the course of ordinary domestic listening? A simple output meter in the speech coil circuit of the loudspeaker will cause eyebrows to be raised!

The writer has recently constructed a three-watt amplifier to a published design and has paid special attention to the problem of feeding a good, clean 3 watts, at all required frequencies, from the output valve anode to the speech coil of the speaker. With this achieved and with a good, wide range, adequately baffled loudspeaker, then the gulf between the 3-watt output and the much more ambitious (and expensive!) " hi-fi " equipment narrows so much that at times it cannot be detected.

The object of this article is to take the reader through the various steps which lead to the successful construction of that vital component, the output transformer. The transformer described is for use in an EL84 output stage; other values of anode current and load impedance would, of course, be used in the calculations as valve and circuit conditions dictate.

First let us see where an inadequately designed transformer fails when used with a single-valve output stage. Fig. 1 is a graph showing how magnetic flux in the core of the transformer increases as current in the primary winding increases. Suppose this winding to consist of 1,000 turns; then 25 mA (.025 A) $\times$ 1,000 gives 25 ampere-turns to magnetise the core, and the graph shows that the core will be magnetised to the point p on the curve where the flux, read on the vertical scale, is 22,500 lines. Increasing current from 0 to 25 mA increases flux proportionately—the graph is a straight line over this part. But whereas increasing current from 10 to 25 mA increases flux from 9,000 to 22,500 lines, i.e., by 13,500 lines, a further equal increase to 40 mA only increases flux by 7,500 lines. This is because at the point p the core is about to saturate and become increasingly less responsive to changes in magnetising ampere-turns.

Now suppose this primary winding to be connected in the anode circuit of an output valve whose steady anode current is 25 mA. The core will be held steadily magnetised to the point p. Then let an alternating current with a peak value of 15 mA be superimposed on the 25 mA D.C. anode current. The valve's anode current will now be rising to 40 mA and falling to 15 mA during each cycle. This is shown on the graph by the wave-form plotted below the horizontal scale. To the right is plotted a wave-form showing how the flux in the core varies in response to the changing anode current. This wave-form can equally well represent voltages across both primary and secondary of the transformer, since voltage is proportional to flux. Obviously, here we have a very distorted picture of the original current wave-form, and at the loudspeaker the transformer's inability to deal with large current and voltage swings will manifest itself by lack of bass, where voltage and current swings are greatest. The damage has been done by allowing the core to saturate; this is largely as a result of the D.C. anode current pushing the working point p too far up the curve. In passing it may be noted that this problem of core saturation does not arise with a push-pull output stage as the ampere-turns due to the anode currents of the two valves cancel each other out. Which is why some push-pull amplifiers are better than they otherwise might be! And having seen one important reason why some single-valve output stages are worse than they might be, the gulf begins to narrow.

First Steps

From the spares-box or among the unused ex-government gear choose an old transformer or choke with a suitable core. It should be appreciably larger than the conventional " loudspeaker transformer," but not quite of mains transformer size. The centre limb might conveniently have a cross-sectional area of ¾ sq. in. There must be sufficient window space for the windings. Fig. 2 shows the core selected by the

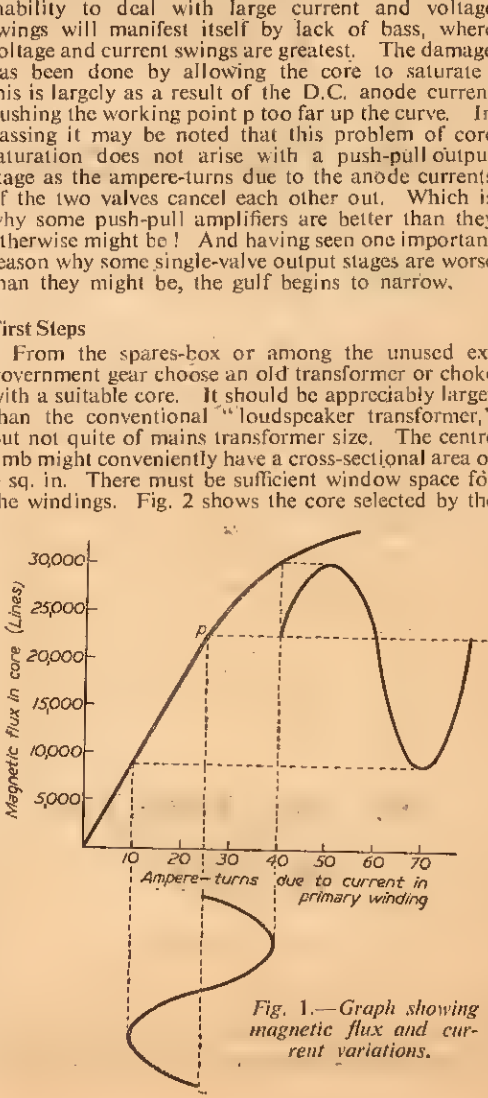

Fig. 1.—Graph showing magnetic flux and current variations.

writer, that of an ex-government, 5 henry 200 mA choke. Remember that more iron in the core means proportionately fewer turns on the windings. Strip the core down, taking particular care of the frame and clamping bolts. Discard the old windings and give it a clean up generally. Pickling in strong caustic soda solution will remove old varnish from frame and bolts. Remove obvious rust from the core laminations, but do not scrape them to expose bright metal. At this stage it would be as well to repeat the fundamental transformer equation to which frequent recourse will have to be made.

$$E=\frac{4.44\ \Phi\ f\ t}{100{,}000{,}000}$$

E = R.M.S. volts across winding.
Φ = Maximum number of lines of magnetic flux reached in each half cycle.
f = frequency in cycles per second.
t = number of turns on winding.

This equation will be rearranged from time to time.

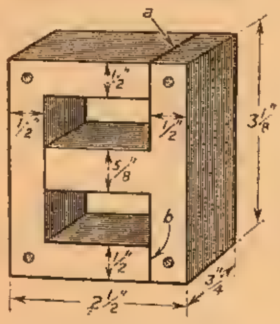

Fig. 2.—Details of the core.

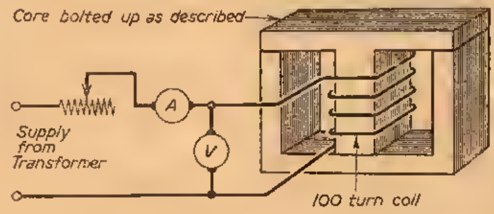

Fig. 3.—The set-up for measuring magnetising current.

Magnetic Measurements on Core

It would be merely groping in the dark to proceed further without reliable knowledge of the magnetic behaviour of the selected core. This will be obtained by actual measurement and the following apparatus will be necessary: an A.C. ammeter, say 0-3 amp.; an A.C. voltmeter, 0-12 volt; a transformer, preferably tapped, giving about 15 volts 2 amp., and a variable resistance about 5Ω and capable of carrying 3 amp. The transformer may present a little difficulty; a receiver mains transformer with valve and rectifier heater windings connected in series would provide rather over 12 volts and tappings as well. The resistance can be improvised by making crocodile clip connection to a length of fire-element or even galvanised wire. The resourceful reader will have no difficulty in arranging gear to give him the necessary readings. One point is important: a separate ammeter is essential; it is useless to expect a single multi-range instrument to serve by disconnecting it as an ammeter when current has been adjusted and then taking the voltage reading.

Make a rough cardboard former to fit the centre limb of the core and on it wind 100 turns of about 20 s.w.g. wire. This is a search coil which will provide a known number of ampere-turns to magnetise the core. It can be wound quite roughly. Carefully reassemble core with the search coil in place. Butt joints between the stampings should be carefully tapped close and the whole core firmly bolted in its frame. Connect it up on the test bench as shown in Fig. 3. The object now is to take a series of readings each giving current through the winding and the voltage set up across the winding. The IR drop in the search coil will be negligible so the voltmeter reading may be taken wholly as volts induced in it by the changing flux. It is ampere-turns that matter rather than the R.M.S. amps. indicated by the ammeter. This point is mentioned as the reader may find it expedient to tap his search coil at, say, 50 turns, and change his tapping as the readings proceed. Start with a small current and increase for each reading until further ampere-turns produce little increase in voltage. Tabulate the readings as shown in Fig. 4 which gives the figures obtained by the writer with his core. These figures will be used in the few simple calculations which follow, so that in working out his design from his own results the reader will have no difficulty in substituting his own figures.

Plot the Curve

The next step is to construct a graph from the figures given in the table. Do this to a conveniently large scale so that there will be no difficulty in taking readings from it. The horizontal scale is marked off in ampere-turns R.M.S. and the vertical scale in volts R.M.S. Make fine neat crosses at the points where the ampere-turns line and the voltage line intersect for each reading. Then draw a fine, evenly curving line through the crosses. Do not worry if some of the crosses lie a little above or below the curve, which should follow an even course through the mean positions of the crosses. Such crosses as lie off this curve merely indicate slight errors of manipulation or reading. This, then, is the magnetisation curve of the chosen core. Fig. 5 shows the magnetisation curve of the writer's core, plotted from the data tabulated in Fig. 4. A further, and extremely useful, vertical scale can now be added to the graph. This will show the value of Φ for any point on the curve, and therefore for any number of ampere-turns. Rearrange the transformer equation thus:—

$$\Phi=\frac{E\times 100{,}000{,}000}{4.44\ f\ t}$$

For E put in the highest voltage reading given by the table (Fig. 4), for f the mains frequency (50), and for t the number of search coil turns in use when the reading was taken. In the present case this gives:

$$\Phi=\frac{9.8\times 10{,}000{,}000}{4.44\times 50\times 100}=44{,}000\text{ lines.}$$

Draw a vertical line to the left of the voltage scale on the graph; carry across to this a line from the point on the voltage scale corresponding to the voltage used in the above flux calculation; mark this point on the flux scale with the value given by the calculation. The vertical distance between this and the horizontal line of the graph must now be divided evenly, say in five thousands, to give a scale from 0 to the calculated flux value. Dividing up this

(*Continued on page 845*)

scale should be quite simple and extreme accuracy is not called for. The completed graph is shown in Fig. 5 and it now presents the "vital statistics" of the core in a readily accessible manner.

Valve Requirements

Consider an EL84 valve delivering 3 watts into a 5,000 ohm load. The equation for power in a circuit is :—

$$W=\frac{E^2}{R} \text{ or } E^2=WR \quad \text{where} \begin{cases} W=\text{power in watts.} \\ E=\text{volts R.M.S.} \\ R=\text{resistance in ohms} \end{cases}$$

putting in values $E^2=3\times5{,}000$

and $E=\sqrt{15{,}000}=123$ volts.

So that at 3 watts output there will be at the anode of the EL84 an alternating voltage of 123 volts R.M.S. superimposed on the 300 volt H.T. supply. This A.C. voltage must, of course, appear across the primary of the output transformer at the lowest frequency which is to be reproduced. For convenience, and a small margin of safety, call it 125 volts.

Having seen what the valve will demand of the transformer primary, turn to the graph again to find out how these demands can be met. With no signal the steady anode current of the valve must magnetise the core to a point at the middle of the straight part of its magnetisation curve. The reader must fix this point for himself on his own graph. In Fig. 5, it is marked at p where the flux is 17,000 lines, and the voltage it sets up across a 100 turn coil is 3.6 volts. This, of course, at a frequency of 50 cycles. These figures will be used again, and should be noted. When the valve is handling a signal, flux will rise and fall above and below this working point value of 17,000 lines by an amount which must be the Φ of the transformer equation.

Looking at the graph, it will be seen that flux cannot be allowed to rise above 32,000 lines, for fear of going "round the bend." For the transformer calculation Φ may, therefore, be taken as 32,000 — 17,000 = 15,000 lines. The reader will obtain his own figure from his graph, the pattern being clear. Sufficient data have now been accumulated to enable the transformer equation to be used to find the number of turns required by the output transformer primary.

$E=125$ volts, $\Phi=15{,}000$ lines, f=lowest frequency to be reproduced—say 40 cycles.

Rearrange the equation thus :—

$$t=\frac{E\times100{,}000{,}000}{4.44\ \Phi\ f}$$

put in values $t=\dfrac{125\times100{,}000{,}000}{4.44\times15{,}000\times40}=4{,}700$ turns.

Now these turns on the transformer primary will be carrying the valve anode current. Take this as 40 mA (.04 A). Multiplying amps. by turns gives $.04\times4{,}700=188$ ampere-turns. The graph shows that these ampere-turns would magnetise the core well beyond the chosen working point. This would be disastrous and will be corrected by introducing an air-gap into the magnetic circuit of the core. But this adjustment will be left until final assembly of the transformer.

The secondary winding must now be considered. The number of turns on this depends on the impedance of the speaker to be used. This impedance appears at the transformer primary winding multiplied by the square of the transformer turns ratio. The ratio of primary to secondary turns on the transformer will, therefore, have to be the square root of the number by which the speaker impedance has to be multiplied to make it equal to the load impedance required by the valve. The formula is :

$$r=\sqrt{\frac{R_L}{R_S}} \quad \text{where} \begin{cases} r=\text{pri/sec ratio.} \\ R_L=\text{valve load impedance.} \\ R_S=\text{speaker impedance.} \end{cases}$$

It is convenient to be able to match either a 15Ω speaker or a 3.75Ω speaker to the valve, so alternative impedance outputs are desirable from the transformer secondary. For a 15Ω output the turns ratio must be :

$r=\sqrt{\dfrac{5{,}000}{15}}=18.3:1$ and for a 3.75 Ω output the turns ratio must be $r=\sqrt{\dfrac{5{,}000}{3.75}}=36:1$.

Dividing these ratios into the primary turns gives for 15Ω, $\dfrac{4{,}700}{18.3}=257$ turns and for 3.75Ω, $\dfrac{4{,}700}{36}=114$ turns. A 257 turn secondary will, therefore, be used, tapped at 114 turns to provide a 3.75Ω output.

Construction

It is not proposed to describe the winding of the transformer in detail. Every serious reader will by now have had some experience of coil winding of this kind and will have evolved his own techniques. The writer made up a bobbin with paxolin cheeks and partition pieces to provide three equal winding spaces. A cement made by dissolving Perspex in chloroform is a very useful adhesive. Cheeks and partition pieces must be adequately supported during winding or they will be pushed out of place. Choice of wire gauge is dictated by the window area of the core stampings. Wire tables and simple arithmetic soon settle this issue. It is essential to keep the D.C. resistance of primary and secondary as low as possible. If, for instance, the resistance of the primary is allowed to be as high as 1,000Ω, then at 40 mA the valve anode will be robbed of 40 volts H.T., and its output considerably lowered.

In addition, power which should be fed to the speaker is dissipated in the primary winding. A secondary winding which is supplying 3 watts to a 3Ω speaker is generating 3 volts to drive 1 amp. through the speaker winding and through itself. If

Search Coil turns ...	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Volts R.M.S.	.8	1.6	2.4	3.15	3.9	4.85	5.6	6.4	7.0	7.6	8.1	8.5	9.0	9.3	9.5	9.8
Amps. R.M.S.	.2	.4	.6	.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.4
Ampere-turns	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	340

Fig. 4.—How the readings are tabulated.

the resistance of the secondary winding is allowed to be as high as 3Ω, current is halved and power loss becomes considerable because of the doubled impedance. Things may not be quite as bad as this, but use wire gauges to fill all available winding space. The writer used 36 s.w.g. enamelled for his primary, which was wound in two sections with the secondary between them. This is desirable in every case to obtain maximum coupling between the windings. The first 114 turns of the secondary (3.75Ω) were wound with 22 s.w.g. enamelled and the remaining secondary turns with 24 s.w.g. With the 15Ω winding current is less, there is more voltage to play with, and the effect of winding resistance not quite so serious.

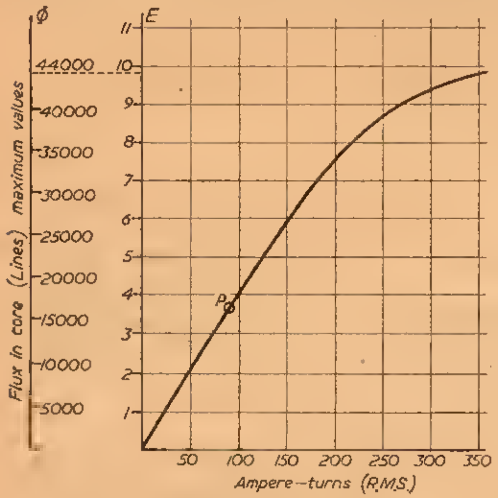

Fig. 5.—The magnetisation curve of the chosen core.

Assembly and Gap Adjustment

Assemble the core around the bobbin with all the "U" stampings facing in one direction and all the "T" stampings in the other. The core is shown assembled in this way in Fig. 2. Where the two stacks of stampings meet, at a and b, insert small pieces of some hard, incompressible insulating material, each about .01in. thick. Thin paxolin will do. The writer used mica; this is convenient because its thickness can easily be built up or reduced. Tap the stampings gently together, compressing the mica in the gaps. Bolt up securely in the frames and connect up to the measuring equipment on the test bench. This time the 3.75Ω secondary winding will be used to provide the known number of ampere-turns which will be exactly equal to those set up by the primary when it is carrying the valve anode current. These will be .04 amp. (for EL84) by number of primary turns. In the present case this is .04 x 4,700 = 188 as noted previously. Now comes a snag, but not an insurmountable one. The curve on the graph indicates the maximum flux value reached during each half cycle of alternating current, because voltage is proportional to maximum value of flux. But the ampere-turns scale is based on the R.M.S. value of the current which is only .7 of the maximum value reached by the current in any half cycle. This means that at the point corresponding to 70 ampere-turns on the scale the flux value shown by the curve is that which is set up at the instant the current is peaking up to 100 ampere-turns. Now, a steady D.C. maintains a steady "peak" value all the time. Therefore, to reach the same point on the curve, using A.C., as would be reached by 188 ampere-turns D.C., it will be necessary to multiply the 188 by .7 and then adjust the search coil current to provide the reduced number of indicated ampere-turns. $188 \times .7 = 132$ ampere-turns to be provided by the 114 turn coil. Dividing ampere-turns by turns to find the amps. required gives $\frac{132}{114} = 1.16$ amps., to which reading the ammeter must be kept while adjusting the core gap. It was noted previously that with flux at 17,000 lines, the chosen working point, the voltage set up across the 100-turn search coil was 3.6 volts. Across the 114 turns the same flux will set up a proportionately higher voltage: $3.6 \times \frac{114}{100} = 4.1$ volts. The stage is now set for the final adjustment of the core gap. This is done by adjusting the thickness of the mica spacing pieces until with 1.16 amps through the 3.75Ω winding a voltage of 4.1 volts is obtained across the winding, and this with the stampings tapped as close as the spacers will permit them and with the core firmly bolted up. Switch off for each adjustment of the spacers and readjust current for every reading.

Your Own Data

When the correct readings have been obtained, check over the frame bolts and test again. In describing the adjustment of the core, flux, voltage, current and ampere-turns figures have been used which relate, of course, to the writer's transformer. All essential substitutions will become obvious to the reader as he takes his own readings and records his own data.