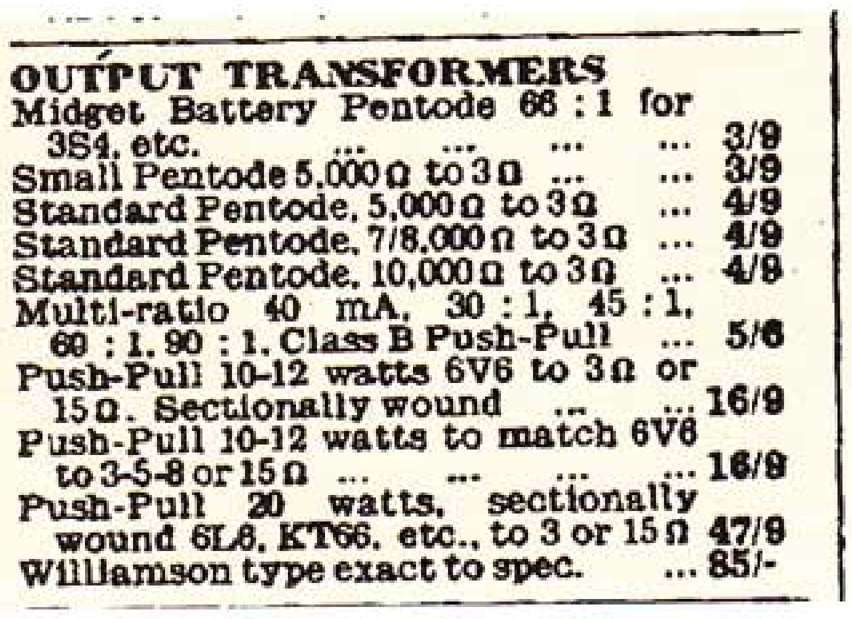
Selecting a Valve Audio Output Transformer

by Stef Ni

If, like me, you have a good selection of valve output transformers that you've picked up for maybe a pound or two each at radio rallies or BVWS meetings, or extracted from old radios when they were beyond practical repair, you may be wondering when exactly you can make use of them. When the time comes to use one, either to replace a failed one in a radio you'r trying to bring back to life, or when building a new valve-based project, it can be difficult to know which one to select. In the 'old days' you would have simply ordered a replacement transformer by post (see Figure 1 for a September 1955 advert for output transformers) but today it's not that easy. This article describes simple methods of testing the transformers you have and assessing their suitability for use with a particular valve output stage.



OUTPUT TRANSFORMERS

Midget Battery Pentode 66 : 1 for 3S4, etc.	3/9
Small Pentode 5,000 Ω to 3 Ω	3/9
Standard Pentode, 5,000 Ω to 3 Ω ...	4/9
Standard Pentode, 7/8,000 Ω to 3 Ω ...	4/9
Standard Pentode, 10,000 Ω to 3 Ω ...	4/9
Multi-ratio 40 mA, 30 : 1, 45 : 1, 60 : 1, 90 : 1, Class B Push-Pull ...	5/6
Push-Pull 10-12 watts 6V6 to 3 Ω or 15 Ω. Sectionally wound	16/9
Push-Pull 10-12 watts to match 6V6 to 3-5-8 or 15 Ω	16/9
Push-Pull 20 watts, sectionally wound 6L6, KT66, etc., to 3 or 15 Ω	47/9
Williamson type exact to spec. ...	85/-

Fig 1: Mail order Ad for output transformers Sept 1955

Fig 3

Below Left, Fig 2: An example of a trans 'flying' leads coming from the secondary transformer is often mounted on the speaker frame so that connections to the speaker are as short as possible.

Left: Fig 3: Air gap on a typical transformer. This is a particularly clear example, but often the gap is covered in paint or dirt and is difficult to see.

Below: Fig 4: A mains-to-6.3V heater transformer which, being about the right size and having four terminals, could easily be mistaken for an output transformer.

Fig 2

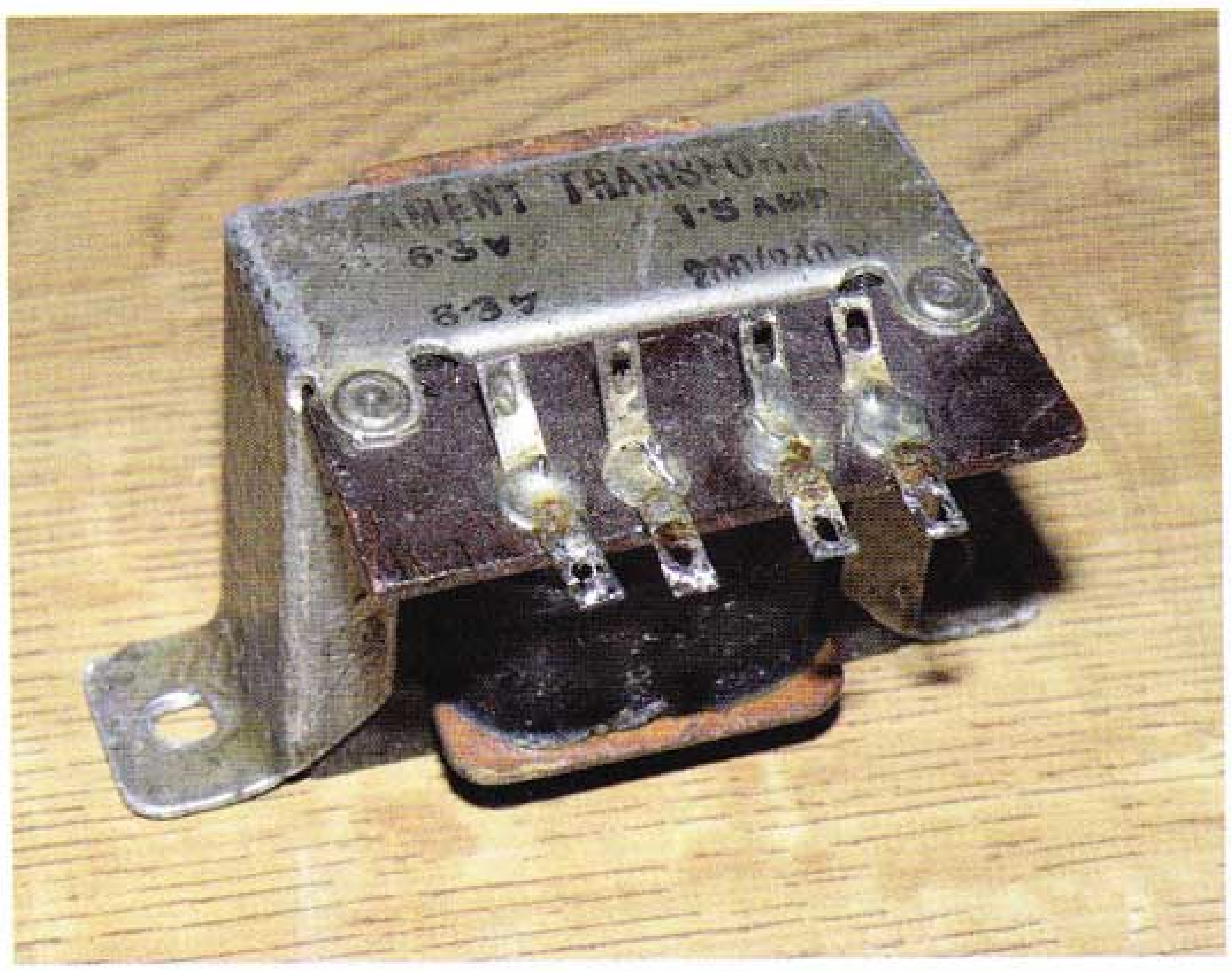


Fig 4

What does the Output Transformer Do?

The main reason why the transformer is there is to perform the impedance transformation from the high impedance (that is, high voltage and low current) valve anode circuit to the low impedance (that is, low voltage and high current) loudspeaker coil, or low impedance headphones. This process results in a matching of the valve's output impedance to the speaker's input impedance, hopefully over a wide frequency range, which results in the most efficient power transfer and best quality sound from the speaker. Note that the term impedance represents the combination of the reactance of any inductance and/or capacitance with any pure resistance in the circuit. In general the impedance of any circuit changes with frequency as the inductive and capacitive components become more and less dominant.

In the 'old days' speakers were produced with high impedance coils, or listeners used high impedance headphones, neither of which needed transformers, and which were connected directly to the anode circuit, most usually in series with a DC-blocking capacitor. Since maybe the mid-1930s, low impedance speaker coils have become almost universal, hence the extensive use of transformers in this application.

Another useful function of the output transformer is to isolate the speaker or headphones from the HT voltage on the output valve's anode, making it safe to plug in headphones or extension speakers.

Some useful notes on valve audio output stages, and what can go wrong with them, can be found in References 1 and 2.

Measure the DC Resistance

It's always handy to carry a multi-meter, digital (DMM) or otherwise, when you're on the look out for transformers and chokes so that you can check the continuity of the windings of any component you are thinking of buying. Reputable stall-holders will always agree to the test, and may even have a meter available themselves in case you've forgotten yours. With an output transformer you're only really out to prove that the windings are still intact, and that the transformer looks a reasonable size for the job it has to do. Sometimes the wire breaks where it comes out from the core, which is a very difficult repair to attempt, or in the middle of the winding, in which case a complete rewind would be the only cure. You should expect to find a primary with a few hundred ohms resistance, and a secondary with a resistance of less that 1Ω. Because one side of the secondary winding is usually connected to ground, it's important that there is no measurable resistance between the primary and secondary windings, which would indicate a breakdown in the transformer's insulation.

A bit of rust on the core and/or the frame of the transformer won't do too much harm, and you can clean it up, straighten out any bent mounting lugs, and apply a coat of paint when you get it home.

Unfortunately the ratio of the DC resistance of the primary and secondary windings isn't

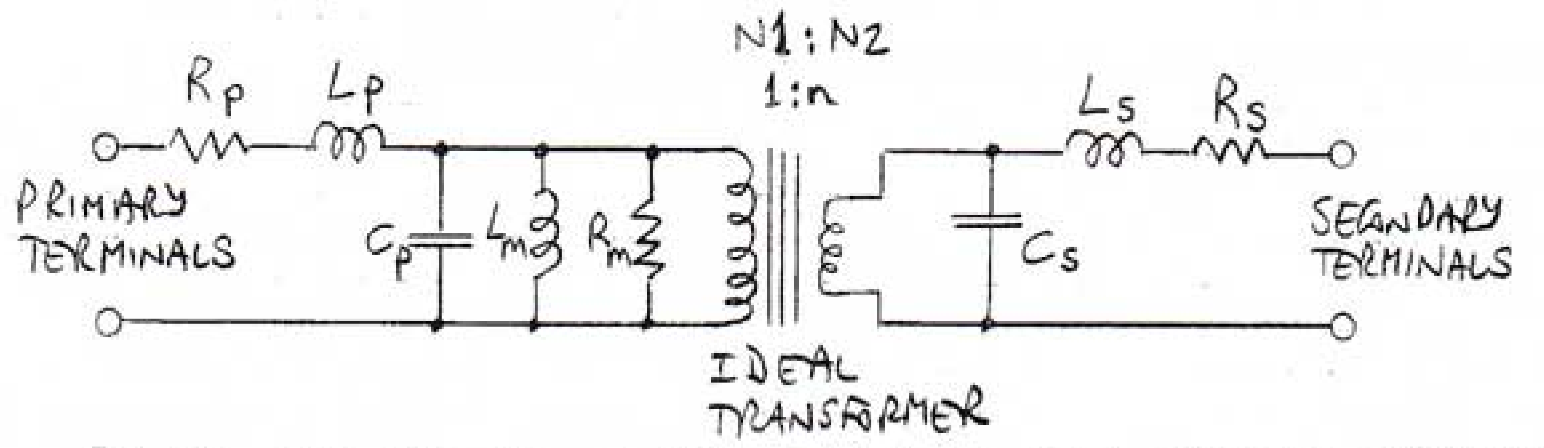


FIGURE 5(a). EQUIVALENT CIRCUIT FOR AN IRON-CORED TRANSFORMER

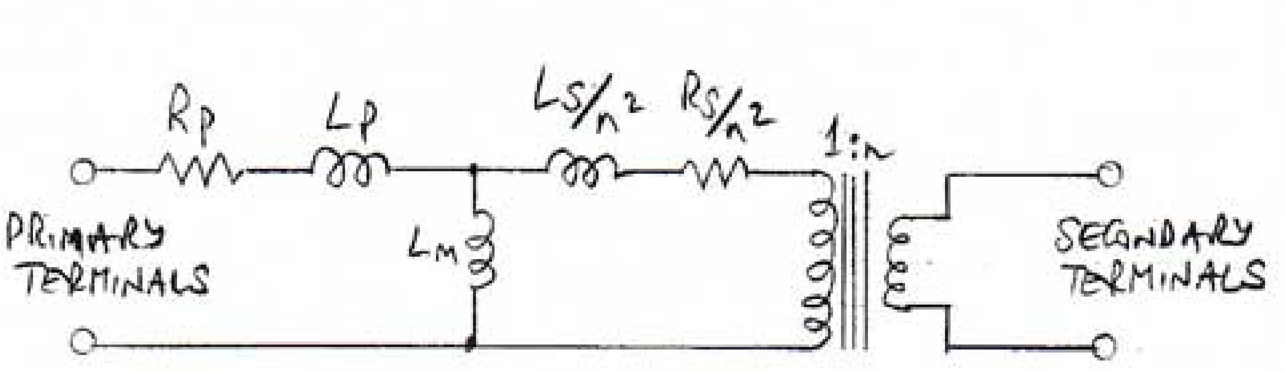


FIGURE 5(b). SIMPLIFIED EQUIVALENT CIRCUIT

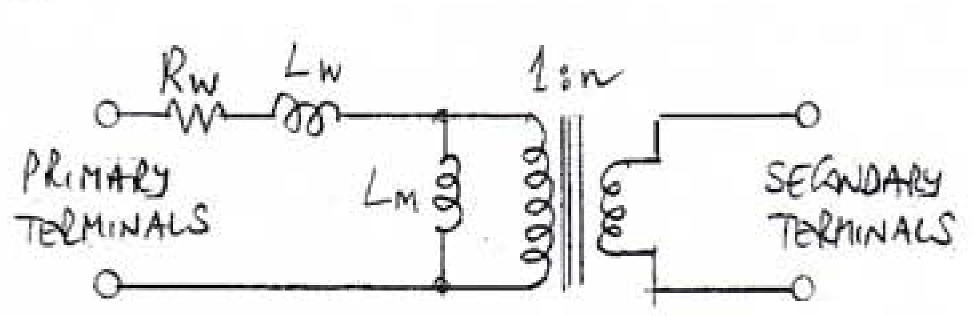


FIGURE 5(c). FINAL EQUIVALENT CIRCUIT

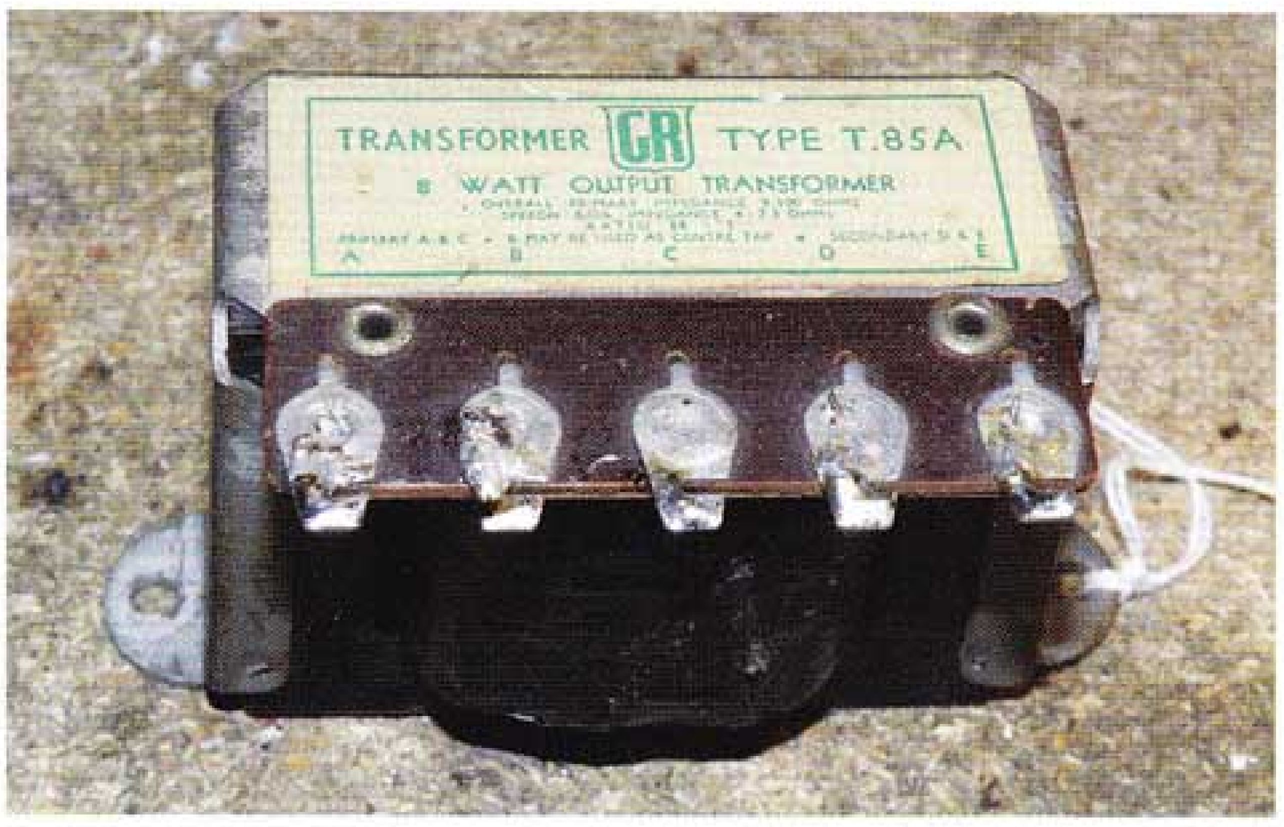


Figure 6: The GR type T.85A 8W output transformer.

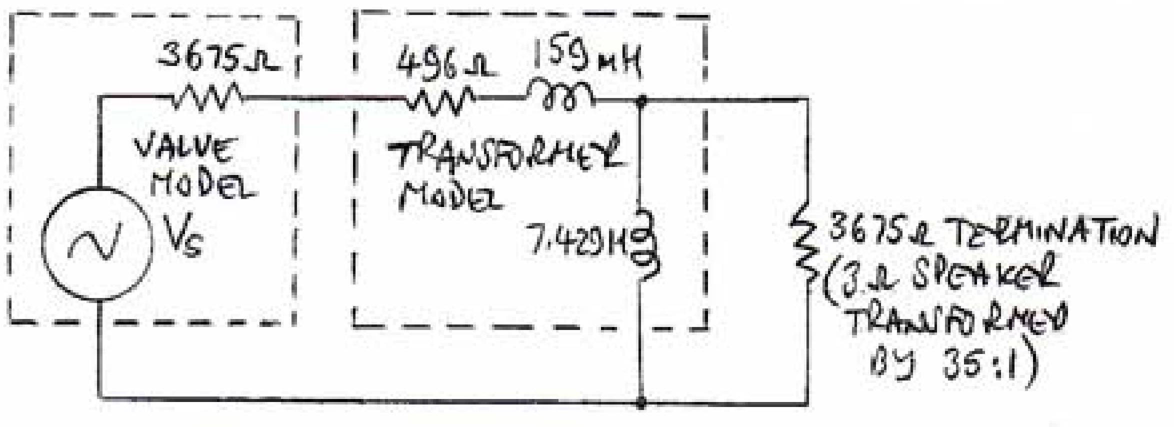


FIGURE 7. SIMULATION MODEL OF VALVE DRIVING 3Ω SPEAKER VIA THE GR TYPE T.85A TRANSFORMER

an indication of the winding ratio of the transformer, otherwise life would be very simple. This is because the two windings will typically be made with different gauge wire. You can often see that the secondary is wound with much thicker wire than the primary, which is what you'd expect since for a given power flow through the transformer, the secondary has to carry more current than the primary.

Sometimes the wire comprising the secondary comes straight out of the winding and connects directly to the speaker, without going through a soldered terminal. I suppose this was a way of reducing the cost of the transformer slightly, and it also has the beneficial effect of eliminating a couple of soldered joints, thereby reducing the chances of dry joints in the path to the speaker. See Figure 2 for an example of a transformer with these 'flying' leads. In some radios the output transformer is mounted on a bracket on the speaker itself, rather than on the radio's chassis, and the unwary can spend a few puzzled moments looking for the transformer above and below the chassis. You may come across a speaker with an output transformer already attached, and if you can negotiate a price of a couple of quid or so, it's generally worth snapping these up to keep for future projects.

Mind the Gap

One of the differences between an output transformer (and a choke for that matter) and a mains transformer is that the primary winding of the former needs to pass some amount of DC current while operating as an impedance translator. This is not true of a mains transformer where the primary is 'excited' by pure AC. In a typical radio the output valve may take an anode current of anything between 1mA (say in valve battery portables) and 25mA or more, which has to pass through the transformer's primary winding, without saturating the transformer, which would have the effect of reducing the inductance of the primary winding. The gap needs to be large enough to prevent this from happening, but not so large that the AC flux has a problem with crossing the gap, which would also tend to reduce the primary inductance and reduce the efficiency of the transformer. A small air gap, typically of the order of a fraction of a mm, in the magnetic circuit solves the DC saturation problem without significantly worsening the AC performance.

See Figure 3 where I've photographed the gap on a small valve output transformer. The gap is particularly easy to see on this transformer: sometimes it's not so easy to spot because it's hidden by the fixing clamp or wax and accumulated dirt.

Beware of Mains Transformers…

You might come across some likely candidates for output transformers, but they could easily be small mains transformers. If they look new, then they probably are 6V or 12V mains transformers (which in themselves can be useful) but some old mains-to-6.3V 'filament' transformers look suspiciously like output transformers. Figure 4 shows such a transformer and being about the right size and weight, and having four terminals, it could easily be mistaken for an output transformer. Hopefully any such transformer you come across will still have its markings intact. Such a 6.3V 'filament' transformer will have a turns ratio of about 36:1, which again is in the right 'ball-park' for an output transformer.

Take a good look for the air gap: if you can't see it, or the seller doesn't know the provenance of the transformer, then it's probably not worth buying.

… but Look out for Chokes

Low frequency chokes are usually easy to identify: they have only two leads or two terminals, since there is only one winding, but again you can look for an air gap which they should have, although it can easily be hidden under paint and the gunge that builds up over the years. Many chokes you come across are ex-MOD components and they are often covered in a black tar-like material, which makes spotting any air gap impossible.

Again it's worth applying the DMM to make sure there's a resistance of a few hundred ohms, which is typical for a mains-driven power supply choke of say 4-10H, across the terminals. If you're keen on valve projects, these chokes of several Henries inductance are very useful for smoothing in power supplies, so it's still worth buying such a component.

Impedance Transformation

A fundamental property of a transformer is to 'reflect' any impedance connected across the secondary winding back to whatever is driving the primary winding. Let's say a transformer has Np turns on its primary and Ns turns on its secondary, then it has a turns ratio equal to Np/Ns , which for an output transformer is usually much bigger than unity. The impedance ratio is equal to the square of Np/Ns. Therefore if the transformer has a turns ratio of 30, then the impedance ratio is 900, and so a 10Ω load on the secondary will be 'seen' as 30^2 times 10Ω = 9,000Ω at the primary.

What's the effect of having no load, that is, an open circuit, across the secondary? This is definitely bad news, especially if the 'volume' is turned up loud, which would probably be the first reaction if nothing could be heard. With no load on the secondary the primary circuit 'sees' a high impedance and this can cause the AC voltage levels to rise to high levels at the anode of the output valve, even to the point of damaging the valve, the transformer and the capacitor often strapped across the primary winding to shape the high frequency response of the amplifier. This capacitor is typically a 0.01µF (or smaller) component, is often rated at 1,000V DC to cope with the high voltage transients seen in this circuit, and

Table 1: Ra (sometimes called Zout) and output power values for some popular audio output valves.

Valve	Close or identical equivalents	Base	Ra or Zout (ohms)	Va (volts)	Output power (W)	Notes
6V6	6AY5, CV510, VT107	Octal	5,000	250	4.5	Class A single-ended.
6V6	6AY5, CV510, VT107	Octal	10,000	250	10	Per pair, in class AB1, push-pull.
6L6	CV1286, VT115	Octal	4,200	350	11	Class A single-ended.
6L6	CV1286, VT115	Octal	6,600	360	26.5	Per pair, in class AB1, push-pull.
ECL80	6AB8, CV10746, LN152	B9A	11,000	200	1.4	Pentode section, class A single-ended.
ECL82	6BM8, 6PL12, CV9167	B9A	5,600	200	3.5	Pentode section, class A single-ended.
UCL82	?	B9A	4,500	200	3.3	Pentode section, class A single-ended.
ECL86	6GW8, CV8297	B9A	5,900	250	4.3	Pentode section, class A single-ended.
EL41	CV3889	B8A Loctal	7,000	250	4.2	Class A single-ended.
UL41	CV1977	B8A Loctal	3,000	170	4	Class A single-ended.
EL84	6BQ5, 6P15, CV8069, N709	B9A	5,200	250	5.7	Class A single-ended.
EL84	6BQ5, 6P15, CV8069, N709	B9A	8,000	250	11	Per pair, in class AB1, push-pull.
UL84	45B5	B9A	2,500	200	5.3	Class A single-ended.
PX4	CV1168	B4	3,500	300	4.5	Class A single-ended.
PX25	CV1040, VR40	B4	5,500	400	6	Class A single-ended.
DL35	1C5-GT, CV1805	Octal	8,000	90	0.24	Class A single-ended. Typically used in battery / mains portables.
DL92	3S4, CV484	B7G	8,000	90	0.27	Class A single-ended. Typically used in battery / mains portables.
DL94	3V4, CV2983	B7G	10,000	90	0.27	Class A single-ended. Typically used in battery / mains portables.
DL95	3Q4	B7G	10,000	90	0.27	Class A single-ended. Typically used in battery / mains portables.
DL96	1P1, 3C4	B7G	13,000	85	0.2	Class A single-ended. Typically used in battery / mains portables.
N18	?	B7G	10,000	90	0.27	Class A single-ended. Typically used in battery / mains portables.
N19	?	B7G	10,000	90	0.27	Class A single-ended. Typically used in battery / mains portables.
N78	CV3711	B7G	7,000	250	4	Class A single-ended.
N78	CV3711	B7G	9,000	250	9	Per pair, in class AB1, push-pull.
N709	6BQ5, 6P15, CV8069, EL84	B9A	5,200	250	5.7	Class A single-ended.
KT61	CV1438	Octal	6,000	250	4.3	Class A single-ended.
1A5-GT	1A5, CV755, DL31, VT124	Octal	12,000	90	0.115	Power output pentode.Typically used in battery / mains portables.
1P1	3C4, DL96	B7G	13,000	85	0.2	Class A single-ended. Typically used in battery / mains portables.
3S4	DL92, CV2370, CV484	B7G	8,000	90	0.27	Class A single-ended. Typically used in battery / mains portables.
3Q5	CV819	Octal	8,000	90	0.27	Class A single-ended. Typically used in battery / mains portables.
3V4	DL94, CV1633, CV2983	B7G	10,000	90	0.27	Class A single-ended. Typically used in battery / mains portables.
6BW6	6061, CV2136, CV4043, CV8048	B9A	5,500	180	2	Minitaure beam power pentode..
6AM5	6P17, EL91, N144	B7G	16,000	250	1.4	Output pentode. Class A single-ended.
50	CV2533, VT50	UX4	4,600	300	2.4	Power output triode.
25L6	CV552, CV553, VT201	Octal	3,000	200	4.3	All-metal beam power amplifier.
34GD5	34GD5A	B7G	2,500	110	1.4	Minitaure beam power pentode..
35B5	?	B7G	2,500	110	1.5	Miniature beam tetrode.
35L6	CV561, CV562	Octal	4,500	200	3.3	Beam power amplifier.
50A5	?	B8B Loctal	3,000	200	4.3	Beam power amplifier.
50B5	?	B7G	2,500	120	2.3	Minitaure beam power amplifier.
50C5	CV1959	B7G	2,500	110	1.9	Minitaure beam pentode..
50L6-GT	50L6, CV2534, CV571	Octal	13,000	110	2.1	Power output beam tetrode.

is a common point of failure in old radios.

In theory at least, the impedance ratio of the transformer is independent of the actual number of turns on the primary and secondary windings: it's just the ratio that matters. In reality this isn't quite true because whether the transformer actually works or not depends on some other transformer fundamentals. I don't intend to cover transformer theory in great detail, but it's worth looking into this in some more detail. Hopefully this will explain why if you need a 10:1 turns ratio transformer (to give you a 100:1 impedance ratio) you can't simply put 10 turns on the primary and a single turn on the secondary, which is a question that puzzles most transformer 'virgins'.

Before I answer this question, let's take a look at speaker and valve impedance.

What is the Speaker's Impedance?

To ensure that the transformer makes a good impedance match, you first need to determine what the impedance of the speaker is. This is usually straightforward and hopefully one of a couple of methods will result in the answer. First of all, look on the speaker itself - it may be marked! If not, measure the DC resistance of the speaker's coil (after disconnecting it from the output transformer, of course). A useful rule-of-thumb is that if you multiply this resistance measurement by about 1.2, you'll get the AC impedance. I measured the resistance of a speaker in my Vidor CN431 'Marquisa' portable at 2.6Ω, so multiplying by 1.2 gives me 3.1Ω, which is pretty close to the 3Ω I suspect it is.

Another way is to consult the maker's original service sheet, or the 'Trader' sheet for the radio and this should tell you the speaker's impedance. It should also tell you the DC resistance of the output transformer's primary and secondary windings (presumably so a service man could check these in case of a suspected fault), but strangely and most annoyingly, not the winding ratio.

See Reference 3 for where you can buy a vast range of makers' and 'Trader' service data from. I'm not associated with the supplier of this DVD-ROM, just a satisfied customer and user of this data.

What is the Valve's Impedance?

To make the impedance transformation calculation you will need to know the anode impedance, often abbreviated to Ra, or sometimes Zout, for the output valve driving the transformer.

When I'm looking for information on valves these days I tend to use two main on-line sources. The first is the Tube Data Sheet Locator (TDSL, see Reference 4), and the second is the National Valve Museum (see Reference 5), to which TDSL often links so that a high quality photograph of the valve in question can be seen. TDSL displays a short form data sheet of the valve, a list of equivalents, and very usefully, often links to several scanned manufacturers' original data sheets for that particular valve.

In Table 1 I've listed a few valves often used in audio output stages, along with their Ra values. You can see the range of

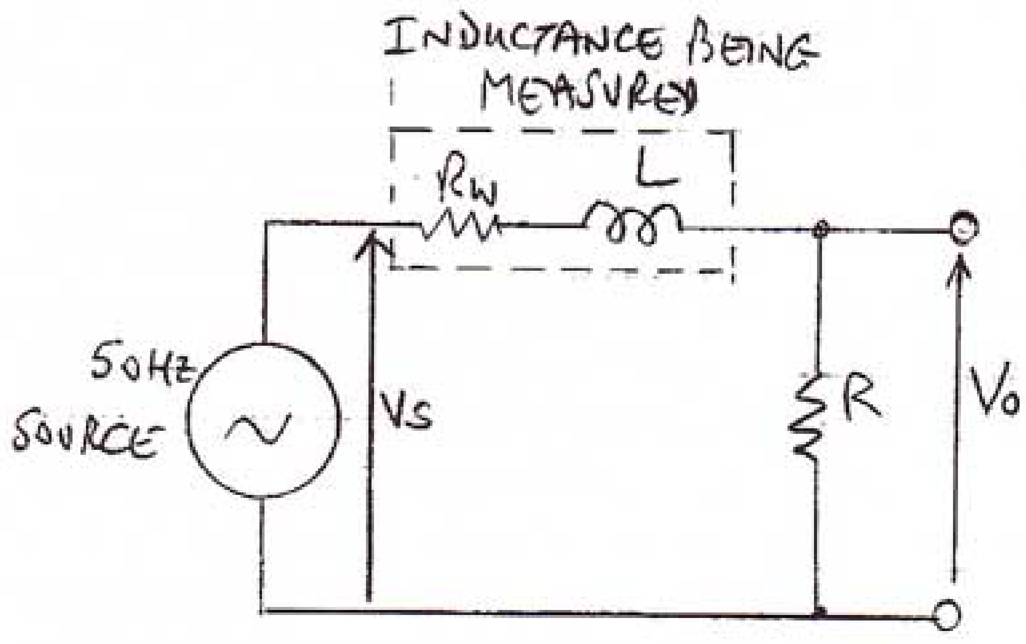


FIGURE 8. SET-UP FOR 'BACK TO BASICS' MEASUREMENT OF INDUCTANCE

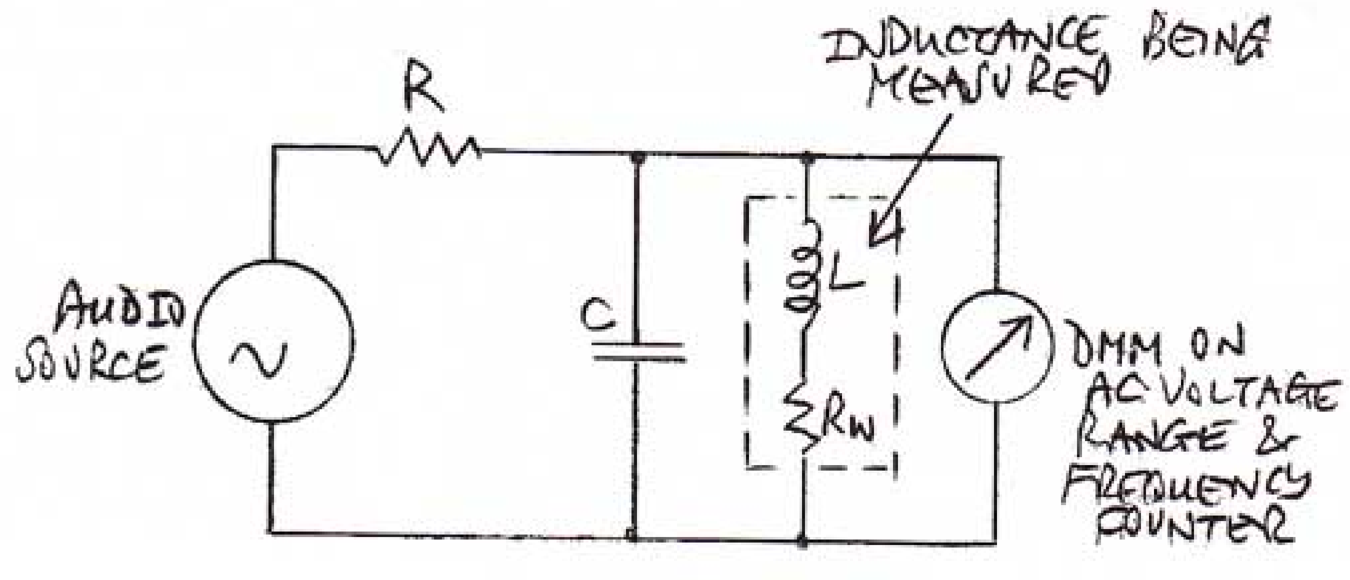


FIGURE 9. SET-UP FOR MEASURING INDUCTANCE BY DETERMINING RESONANT FREQUENCY WITH A PARALLEL-CONNECTED CAPACITOR

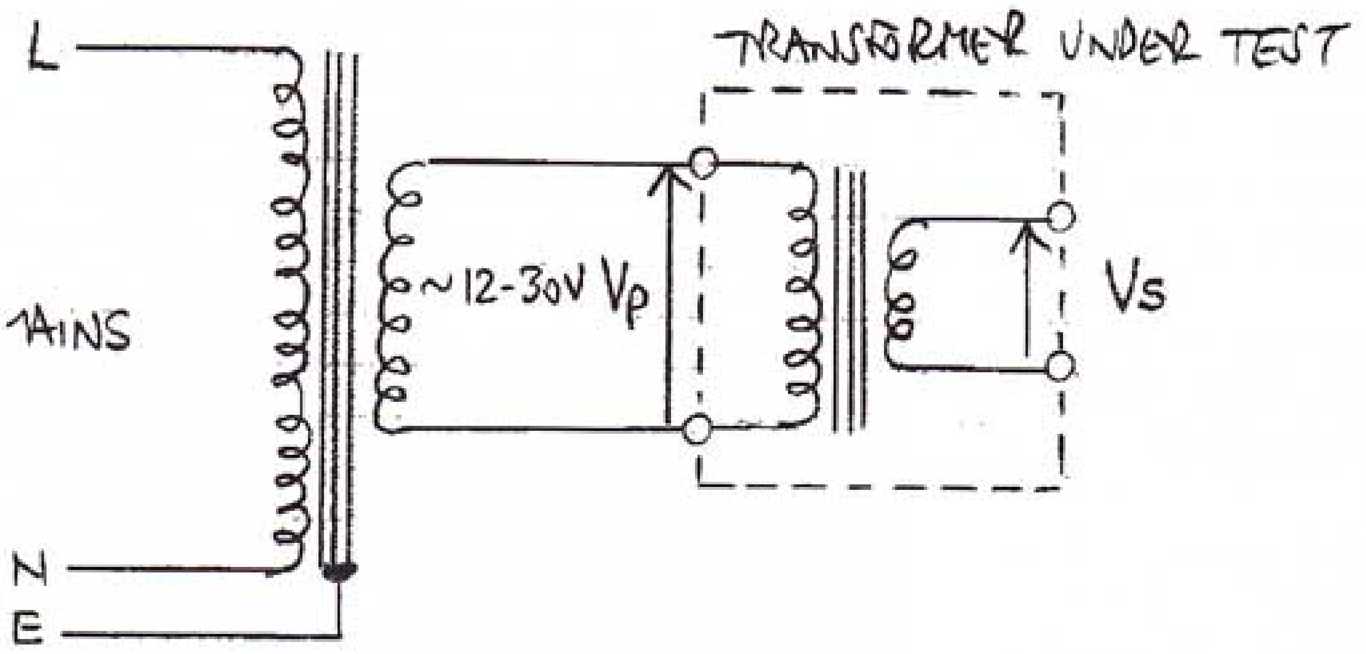


FIGURE 10. TEST SET-UP FOR MEASURING TRANSFORMER TURNS RATIO AT 50HZ

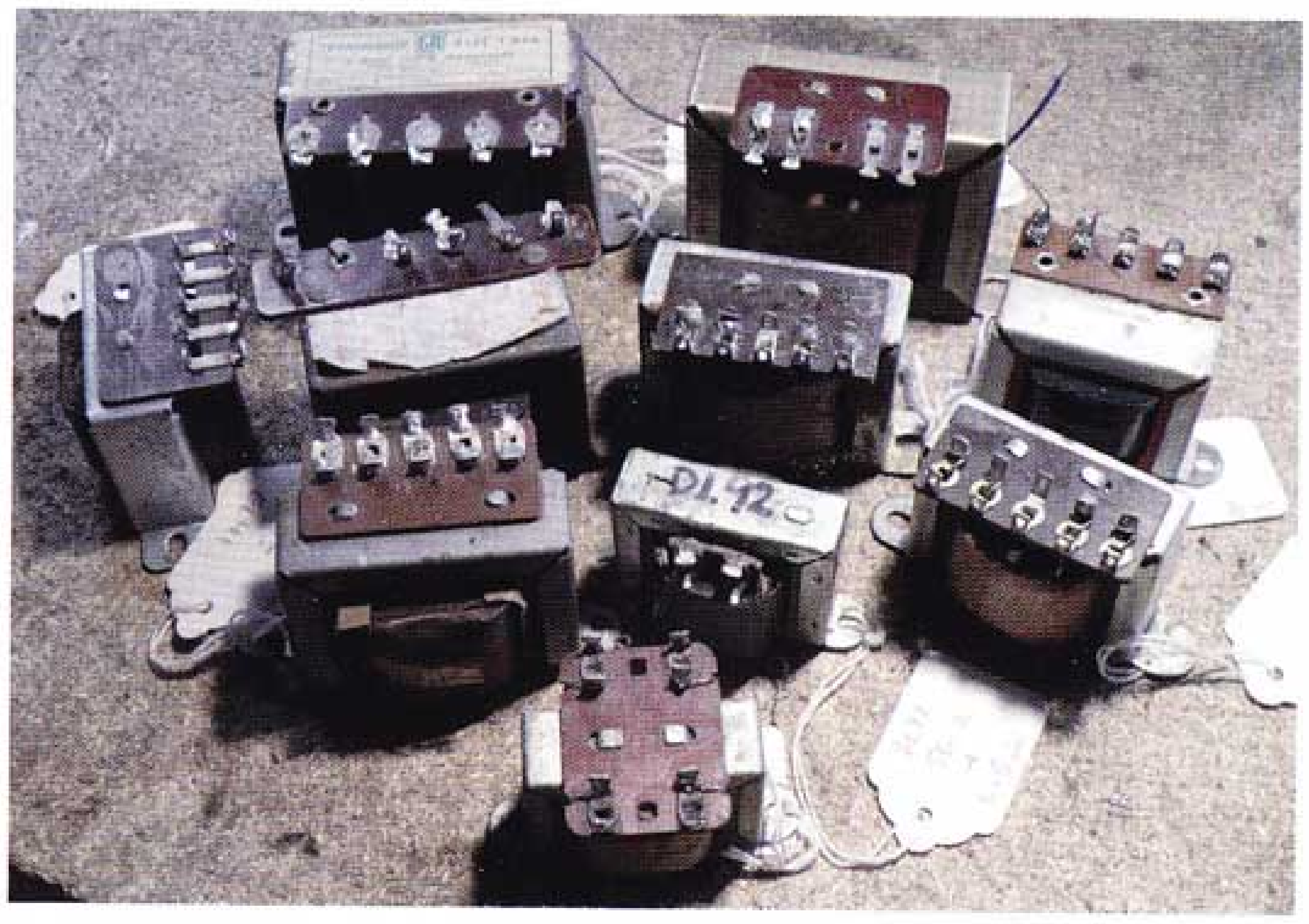


Fig 11: A 'family portrait' of the transformers I tested

typical values, from about 2.5kΩ to 13kΩ. I've tried to limit the list to valves you might find in a typical 'table' or portable radio, and medium power/quality amplifiers, but I have not included valves normally found in Hi-Fi or 'classic' guitar amplifiers (for example, Marshall, Fender, Gibson, etc), such as the EL34, KT66, and so on. Those who repair and restore these pieces of equipment will probably have their own ideas about how an output transformer should be replaced or rewound, to maintain the 'sound' and frequency response (typically 20Hz – 20kHz) of the original. If your valve isn't there, then take a look in the reference sources above, or I've shown a few other sources at the bottom of this article.

Primary Inductance and Equivalent Circuits

It is fairly commonly known that any output transformer must have a reasonable value of primary inductance for the best frequency response. But why is this so, and what does 'reasonable' mean in this context?

Figure 5(a) shows a typical equivalent circuit of a transformer (taken from Reference 6). What exactly is an 'equivalent circuit'? In general terms, it is an electrical model of how a component (in this case a transformer) behaves in practice, and is usually the basis of a simulation model so that, for example, the frequency response of the component can be predicted using an analogue simulator such as Spice. A component that is typically complex to predict its behaviour (like a real life transformer) is reduced to a grouping of several much simpler models (like ideal resistors, capacitors and inductors) which are measurable (in theory at least, see later). Another example of a useful equivalent circuit is that of a quartz crystal, where the complex mechanical behaviour is again modelled by an equivalent group of ideal resistors, capacitors and inductors. Note that an equivalent circuit isn't a kind of a 'breakdown' of what is actually inside the complex component: it is purely a model.

In Figure 5(a) the components represent the following properties of a generic transformer:

On the primary side:
Rp = primary winding resistance (often called 'copper losses')
Lp = primary leakage inductance
Cp = primary winding capacitance
Lm = primary mutual inductance
Rm represents core losses (ie, hysteresis and eddy current losses, often called 'iron losses')

On the secondary side:
Cs = secondary winding capacitance
Ls = secondary leakage inductance
Rs = secondary winding DC resistance (often called 'copper losses')

The transformer in the equivalent circuit is an ideal N1:N2 (or 1:n, where n= N2/N1) component.

Clearly this is quite a complex model and it would be helpful if it could be simplified. The equivalent circuit can be simplified by making some reasonable assumptions: for example the winding capacitances Cp and Cs can be assumed to be very small for most practical purposes and so in our model we will assume they are zero. Also let's trust the designer of the transformer and assume that it is fairly efficient and therefore Rm, representing core losses, can be removed. It would also be handy if we could bring the components connected to the secondary winding over to the primary side, by transforming their impedances by the ratio of the transformer, and this has been done in the modified circuit of Figure 5(b).

A further step can be taken by merging some of the components to give the final circuit of Figure 5(c), where:

$Lw = Lp + Ls / n^2$
and
$Rw = Rp + Rs / n^2$

The model now contains quantities, or parameters, we can measure. For simulation purposes we could even omit the ideal transformer altogether, as long as we terminate the circuit in the transformed load impedance, as would be 'seen' by the primary circuit.

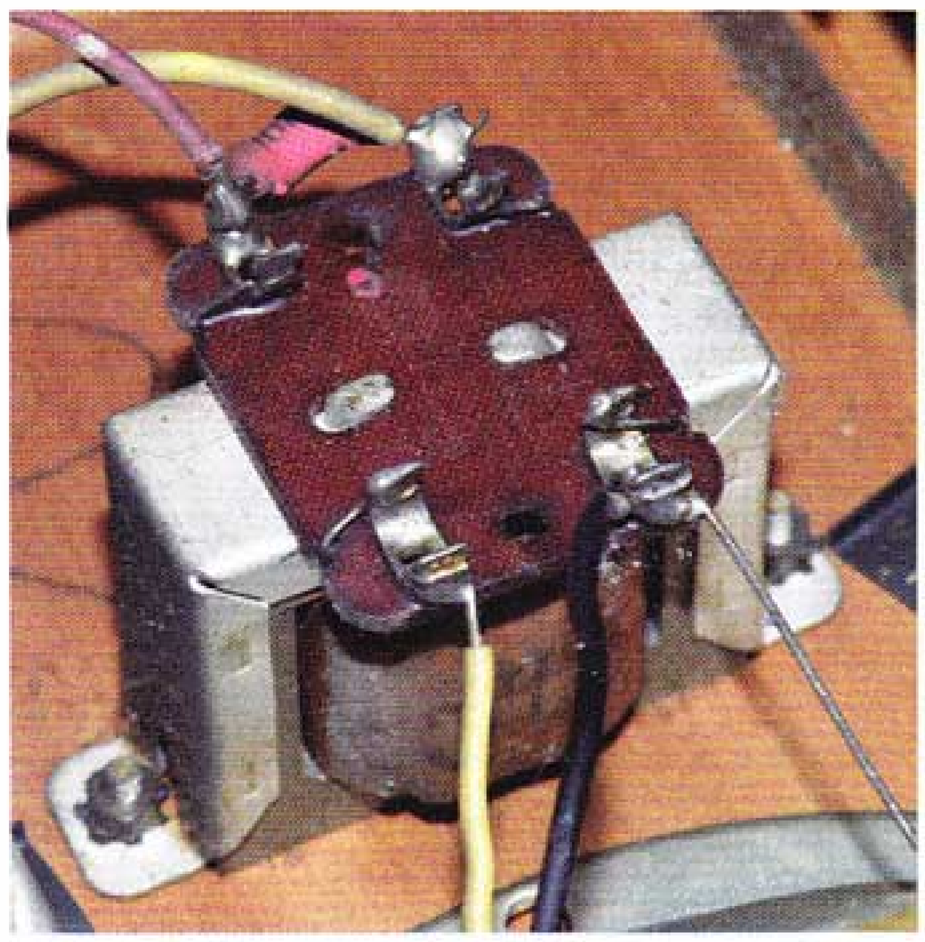
The neat thing about 'moving' the components representing the secondary winding over to the primary side is that we can now just make measurements on the primary side to determine Rw, Lw and Lm and then go ahead and simulate the transformer to see how it behaves over a certain frequency range.

You can see from Figure 5(c) that the mutual inductance of the primary winding (Lm) of the real transformer is connected in parallel with the primary of the ideal transformer and so since for an inductor, $XL = 2\pi fLm$, for any given frequency, the greater the value of Lm, then the greater the value of XL and therefore

Table 2: Summary of Test Results							
Inductance Measurement							
Method Used	**Admiralty choke**	**GR Type T.85A**	**Transformer no. 3**				
Peak Atlas LCR Meter	5.34H @ 1kHz	7.43H @ 1kHz	2.922H @1kHz				
4070L LCR Meter	5.47H @ 100Hz	8.91H @27Hz	3.66H @27Hz				
Reference 8 Method (Figure 8)	7.5H @ 50Hz	22H @ 50Hz	9.4H @ 50Hz				
Resonant Frequency Method (Figure 9)	5.55H @ 700Hz 4.88H @ 210Hz	8.58H @ 169Hz 8.60H @ 527Hz	3.44H @ 267Hz 3.27H @ 854Hz				
Transformer / Choke Tests							
Transformer / Choke Tested	**Primary DC resistance (ohm)**	**Secondary DC resistance (ohm)**	**Primary Inductance (H) with sec o/c**	**Primary Inductance (mH) with sec s/c**	**Mutual Inductance / Leakage Inductance**	**Turns Ratio**	**Weight (gms)**
'6H' Admiralty choke	142	Not applicable	5.34	Not applicable	Not applicable	Not applicable	750
Transformer GR Type T.85A	496	0.6	7.43	159	46.7	35:1	620
Transformer no. 1 DL92 Battery	529	0.2	9.23	216	42.7	90:1	170
Transformer no. 3 'small pentode?'	272	0.5	2.92	75.8	38.5	45:1	270
Transformer no. 8 Vidor CN431 DL94	608	0.3	6.86	177	38.8	57:1	180
Transformer no. 6 UCL82	438	0.4	5.39	151	35.7	38:1	280
Transformer no. 9 'small pentode?'	272	0.3	2.48	70.4	35.2	30:1	180
Mains - 6.3V transformer	320	0.8	6.62	126	52.5	35:1	340

Table 3: Vrms values for a series of speaker impedances and output powers. Note: this is the RMS voltage across the secondary winding. The voltage across the primary will be greater by the factor of the winding ratio.

R (ohm)	P (W)	Vrms	R (ohm)	P (W)	Vrms	R (ohm)	P (W)	Vrms
3	0.25	0.87	8	0.25	1.41	15	0.25	1.94
3	0.50	1.22	8	0.50	2.00	15	0.50	2.74
3	0.75	1.50	8	0.75	2.45	15	0.75	3.35
3	1.00	1.73	8	1.00	2.83	15	1.00	3.87
3	1.50	2.12	8	1.50	3.46	15	1.50	4.74
3	2.00	2.45	8	2.00	4.00	15	2.00	5.48
3	3.00	3.00	8	3.00	4.90	15	3.00	6.71
3	5.00	3.87	8	5.00	6.32	15	5.00	8.66
3	7.00	4.58	8	7.00	7.48	15	7.00	10.25
3	10.00	5.48	8	10.00	8.94	15	10.00	12.25



Above, right Fig 12: The Vidor CN431 portable DL94 output transformer. The power output from this set is only 270mW and so the transformer is very compact and light.

the smaller the 'shunting' effect this has on the signal passing through the transformer. As the frequency gets higher, even a smallish inductance has a high reactance and therefore Lm has the greatest effect on the low frequency response of the transformer, typically what goes on below say 200Hz.

Similarly Lw is in series with the primary of the ideal transformer and so we want the value of Lw to be as small as possible so that it contributes as small an reactance as possible in this series path. Again as frequency gets higher, even a smallish inductance has a high reactance and therefore Lw has the greatest effect on the high frequency response of the transformer.

Even a fairly complex equivalent circuit (and I classify the transformer model in this category) may in itself be a simplification of the real world. For example the transformer equivalent circuit makes the assumption that the circuit elements, and therefore the transformer itself, behave linearly over a large range of voltage amplitudes, and that the circuit element values do not change over frequency. Neither of these assumptions is likely to be true in real life, but the model is close enough to give results accurate enough for most practical purposes.

Measuring the Transformer's Parameters

So let's look at how we measure Rw, Lw and Lm. In fact with the right instrument these can be measured very easily by two simple measurements of the primary winding, one made with the secondary open circuit and the other with the secondary short circuited.

I have a Peak Atlas LCR40 component meter, which I bought a few years ago, which is a very useful and compact instrument. I measured the primary parameters of a GR Transformer Type T.85A (see Figure 6) which I picked up at a BVWS meeting a while ago, with the secondary open circuit and then short circuited, using the LCR40. The results were:

Primary Inductance	Resistance	Secondary
7.429H	496Ω	Open circuit
159mH	496Ω	Short circuit

The LCR40 automatically 'decides' the best frequency at which to make these measurements, and for this component it 'chose' 1kHz.

From these measurements we can say that for this transformer:

Rw = 496Ω
Lw = 159mH
Lm = 7.429H

Now we can substitute these values into the equivalent circuit, giving the circuit shown in Figure 7. As well as showing the transformer model, this diagram also shows an AC driving source, Vs, with its source resistance, and a terminating resistor. Note that the ideal transformer has been removed and the terminating resistor value of 3675Ω represents a 3Ω load transformed by the square of the turns ratio of the transformer (in fact about 35:1, see later for how this was determined), and that I have made the driving impedance equal to this same value. I simulated this circuit using LTspice IV (available free of charge by courtesy of Linear Technology, see Reference 7) and the model indicated -3dB points for the transformer to be at about 40Hz and 20kHz, which indicate a good quality transformer.

As you can see from Table 1, 3675Ω looks a little on the low side for a typical pentode output stage, although a 6V6 (at 5kΩ) or a 6L6 (at 4.2kΩ) aren't too far away. Setting the driving impedance to that of an EL41 (7kΩ, and keeping the terminating resistor value the same at 3675Ω) gave -3dB points at about 52Hz and 11kHz, which is still a reasonable response despite the impedance mismatch.

So hopefully that explains why transformers have to have lots of turns on the primary winding: in general, the more turns on the primary then the higher the primary inductance and the better the low frequency response. Of course having more turns makes the transformer bigger and more expensive, so there's definitely a compromise that has to be reached which the transformer designers at GEC, Pye, Ekco, Philips, etc, knew very well, always working to a tight overall cost budget for their sets.

Other LCR Meters

I've recently acquired a digital LCR meter, type 4070L, bought from China via eBay at what I think is the very reasonable price of £15. Maplin stock a DMM with capacitance and inductance ranges, but if you want these along with voltage, resistance and current, then the meter can cost in the region of £50. It seems to be much more cost effective to buy the LCR meter as a separate item.

The 4070L LCR meter also automatically 'decides' on the test frequency: for inductance it makes the measurement at 100Hz. There are other 'professional' LCR meters available, with prices in the £200-£300 range, but I'm not sure they are good value for money for amateurs.

Having a meter like the Peak Atlas LCR40 component meter made the act of measuring the inductance and resistance of an inductor very easy: you just connect up the inductor, press the 'Test' button, wait for about five seconds and there both values are. The LCR40 has the advantage that it automatically compensates for the capacitance and inductance of its leads, which is useful when measuring very small values. Using a more modern LCR meter such as the 4070L, is even easier and the inductance answer appears immediately.

'Old Fashioned' Methods of Measuring Inductance

Unlike resistance and voltage, inductance is a quantity most of us don't measure very often, and in fact most meters (digital or analogue) don't have convenient inductance ranges we can switch to, and you may not possess an LCR meter like the Atlas LCR40 or the 4070L. As I found out when investigating a few methods of measuring inductance, it turns out to be a rather elusive quantity, the value of which seems to depend on how you measure it. In the context of output transformers the exact value of the primary inductance isn't too important, as long as it's reasonably high, as explained earlier.

I thought I'd try a couple of 'old fashioned', back to basics, methods for measuring inductance suitable for those who do not possess LCR meters. Using these methods, you need a little maths to get the final answer but it's not too fearsome. 'Classical' LCR meters consist of bridges where the component being measured is compared with a known 'standard', whether this is a resistor, capacitor or inductor. Since I didn't have a known 'standard' inductor (unless I believed the value from my two LCR meters), I rejected this method.

Figure 8 shows my set-up for a 'back to basics' measurement of inductance. For the AC source I used the nominally 12V winding on a mains transformer, so Vs was about 12.5V AC. The resistor, Rw, in series with the inductor represents its winding's DC resistance. R completes the circuit, across which the output voltage, Vo, is measured. You can see that the reactance of the inductor, in series with Rw, forms a potential divider in association with R. The full maths of how the value of the inductance is calculated can be seen in Reference 8, but the value of L in Henries is given by:

$$L = \frac{\mathrm{Sqrt}\ [(R/x)^2 - (Rw + R)^2\ ]}{2\,\pi\,f}$$

where: $x = Vo / Vs$

When I have a number of calculations to make I tend to make a table in Microsoft Excel of the results and enter the equation in a cell that calculates the answers. I find this saves lots of time. Of course you can simply use a calculator if you don't have access to Excel. See Table 2 for the results obtained for this method. The results don't seem to correspond with those obtained from the LCR meters. See later for why this might be so.

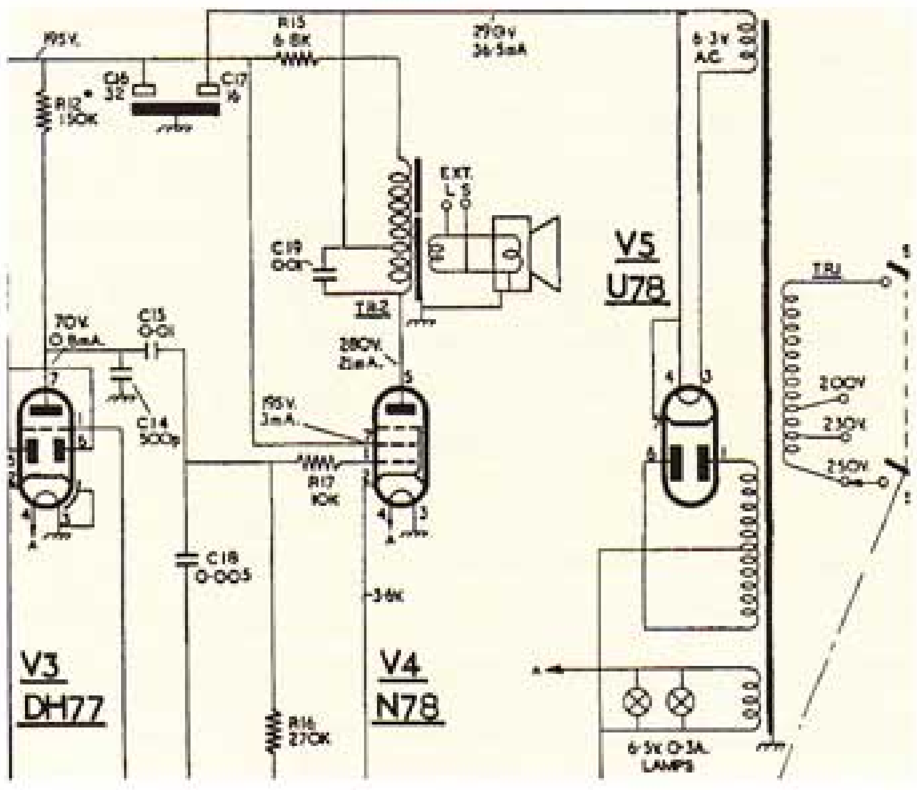


Fig 13: The arrangement used by GEC in its BC5445 radio to combine the audio output transformer and the power supply smoothing choke.

Measuring Inductance by Resonance

Another way to measure the primary (and the secondary for that matter) inductance of a transformer is to determine its resonant frequency when connected in parallel with a capacitor. Figure 9 shows my set up for making this measurement. An audio source (an old Heathkit Sine-Square Wave Generator in my case) drives the parallel-connected capacitor and inductor (represented by an inductor and a series resistor, Rw, representing its DC resistance), and the AC voltage developed across them is monitored by a DMM switched to its AC voltage range. As the frequency is varied a point is found where the voltage across the parallel tuned circuit is at a maximum. The value of the drive resistor, R, isn't too critical and I found with it set to 33kΩ the peak in voltage was quite sharp and easy to spot on the DMM. Once the point of resonance had been found I connected a digital frequency meter across the DMM to measure the exact frequency. Because we are dealing with relatively low frequencies and high values of parallel capacitance and inductance, the input capacity and lead inductance of the DMM and frequency counter make very little difference to the resonant frequency.

These days, some DMMs are capable of measuring frequency directly, which would simply need you to change range on the instrument. You may not need to make this frequency measurement if you're confident of the calibration of your audio generator.

The value of the inductor is found simply from the formula:

$$L = \frac{1}{4\,\pi^2\,f^2\,C}$$

You may have noticed that the equation above makes no mention of Rw, the inductor's DC resistance. I carried out a few simulations to see how a comparatively small value of Rw affected the resonant frequency of the parallel tuned circuit and the effect was negligible, hence why it is ignored in the formula. You may recognise Rw as being a measure of the 'Q' of the inductor and the major effect of a reduction in 'Q' is a flattening in the amplitude peak around the resonant frequency.

The problem of measuring inductance is now reduced to measuring frequency (which is measured using a frequency counter, or with a 'modern' DMM) and capacitance. Again many low cost modern DMMs have capacitance ranges, but if you do not possess a DMM with such ranges, you can probably simply trust the marking on the capacitors you use. I measured a couple of new metallised polystyrene film capacitors (obtained from the BVWS) and 0.01µF and 0.1µF capacitors actually measured 10.6nF and 103.4nF respectively, so using the marked value isn't going to spoil the inductance measurement by too much.

Again I 'programmed' this formula into Excel, but a calculator is perfectly acceptable.

One neat feature of this approach is that you can choose the frequency at which you are measuring the inductance by selecting a capacitor value that resonates at that frequency. In practice it's best to choose several capacitor values, measure them, make the resonance tests and plot a graph of inductance versus frequency to make sure you cover the frequency points or range that you are interested in.

Again, see Table 2 for the results obtained for this method.

How to Determine the Turns Ratio

We know that the turns ratio of a transformer is key to knowing its impedance transformation ratio, so presented with a fairly anonymous transformer, how do we find out what the turns ratio is? It would seem that all we need to do is to apply a known primary voltage and measure the secondary voltage, and calculate the ratio of these voltages. I thought I'd start by testing a 'known' quantity in the form of the GR Transformer Type T.85A mentioned above, which helpfully states on its label:

8 watt output transformer
Overall primary impedance 8,500Ω
Speech coil impedance 4 – 7.5Ω
Ratio 38:1

Figure 10 shows the test set-up I used to measure the turns ratio of this transformer. T1 is a standard mains transformer: I used a nominal secondary voltage of 12V for my tests, but somewhere between 12V and 30V should be OK. Do not even think about connecting the output transformer directly across the mains. This would be very dangerous.

Of course this test set-up results in the transformer being tested at 50Hz, which is probably below the reasonable operating frequency for these mostly non-Hi-Fi transformers. I thought I'd test a couple of transformers at 400Hz, which is the standard frequency at which many speakers' impedances are specified, and is also well within the band of frequencies at which the transformer would be expected to work well, to see if there was much difference from the 50Hz value.

With smaller transformers the effective turns ratio at 50Hz was about 10% higher than at 400Hz, indicating a drop off in performance of the transformer at the lower frequency. This is because at 50Hz the secondary voltage was lower for a given primary voltage than at 400Hz, and so the step down ratio, and therefore the effective turns ratio, looks higher. It is therefore recommended that if the 50Hz value is measured (which is probably much more convenient than making the measurement at 400Hz), you simply add on 10% to this value to give the 'true' turns ratio.

The Test Results

I tested a number of transformers for winding resistance, inductance and turns ratio. There were ones I knew the origin of (for example one from a Vidor CN431, which uses a DL94 output valve; one with 'DL92' and another with 'UCL82' written on them), and others of unknown origin picked up at rallies, etc. I also measured the inductance of an ex-Admiralty choke which was conveniently marked 'Adm Patt W3662A 6H 70mA 140Ω', so it was a good indicator of whether the inductance measurements were giving reasonable results. See Figure 11 for a 'family portrait' of the transformers I tested, and a few others. The results of these tests are shown in Table 2.

The 'Inductance Measurement' section of the table shows the results for the Admiralty choke, the GR Type T.85A transformer and an anonymous small pentode output transformer, which I had labeled 'no. 3'. As you can see the results correspond pretty well, except for what I call the 'Reference 8 Method', so I suspect there's either an error in the formula, or more likely, I've measured or calculated something incorrectly. This shows the value of making measurements by various methods, rather than blindly accepting a single set of results. The variation of the inductance measurements for each component is interesting: you certainly wouldn't expect that spread for example when making a measurement of resistance. But let's remember that these inductance measurements are made at difference frequencies and voltage amplitudes, both of which are likely to affect the results.

The ratio of mutual inductance (that is, the primary inductance measured with the secondary open circuit) to the leakage inductance (that is, the primary inductance measured with the secondary short circuited) works out pretty consistently between about 35:1 and 47:1, across all the output transformers tested. The GR Type T.85A had the highest value, at about 46.7:1, indicating a high quality transformer, which I'm defining as one with high mutual inductance and low leakage inductance, but the others didn't lag behind by too much.

The measured turns ratio of 57:1 for the Vidor CN431 DL94 transformer (see Figure 12 for a photograph of this compact transformer), to give an impedance transformation of about 3250:1 (that is 10kΩ to 3Ω), looks correct, whereas the DL92 transformer measured turns ratio, at 90:1, looks on the high side. Maybe I need to check that result again. It looks like I've got a good selection of turns ratio with the other transformers. You can see from the measurements that the mains-to-6.3V transformer 'looks' remarkably like an output transformer and would probably work pretty well in this role as long as the DC current through the primary was kept at a low value.

For transformers where I tested the turns ratio at 50Hz and 400Hz, the value given in this table is the average of the 50Hz and 400Hz values, though typically they varied by only about 10% in the worst case.

I've also shown the weight (in gms) for each transformer, so you can get an impression of the size of each of them. After testing each transformer I attached a tie-on tag with an identity number and the measured details (winding resistance, inductance and turns ratio) written on it so that I could access the information quickly next time I needed a transformer.

Multi-Tappings

Radiospares (and others) sold replacement output transformers with multi-tappings on the primary and secondary windings to suit 3/8/15Ω speakers and various primary impedances between about 4kΩ and 15kΩ. These are very useful and so if you see one, it's worth snapping up. It probably won't match the style and appearance of the original, but it's quite possible you could hide it beneath the chassis and leave the failed original transformer unconnected in place for cosmetic purposes.

Push-Pull Amplifiers

Higher power and higher quality amplifiers often have a pair of output valves in a push-pull arrangement, driving the primary of a single output transformer. In Table 1 I have shown push-pull (as well as single ended) values of Ra (or Zout) for valves which are commonly used in push-pull mode, though they not very often encountered in domestic radios. I suppose the closest you would get to this in domestic usage would be in a good quality radiogram. It is this value of Ra that the output transformer needs to match to the speaker impedance.

Push-pull transformers are usually wound so that the magnetic flux from the DC current components feeding the anodes of the two valves cancel out, and therefore they do not normally have an air gap.

Transformers for push-pull amplifiers are still available new and second hand on the internet (eBay and other sites): don't be surprised by the high prices they command, especially ones with 'ultra linear' tappings on the primary.

Power Rating of the Transformer

Table 3 shows the secondary voltage (expressed as an RMS value) for various values of power delivered to the load, for different load impedances. Clearly this power 'passes through' the transformer and so it has to be capable of handling this. Note that this isn't the same as saying that the transformer dissipates this power: clearly it doesn't, otherwise no sound would come out of the speaker.

There are analytical ways of assessing the power handling capacity of an output transformer, which take into account the cross sectional area of the core, the core materials, etc, but we'll take the simple pragmatic approach that you should use a replacement transformer at least as big as the original. If you're constructing a valve radio from new, then use the biggest transformer you can fit in, consistent with it's having the correct winding ratio of course, unless you only want to drive headphones, in which case a small transformer should do the job.

Combined Output Transformer and Smoothing Choke

One clever way radio manufacturers saved cost was to combine the audio output transformer and the power supply smoothing choke. Figure 13 shows the arrangement used by GEC in its BC5445 radio, and you will find this arrangement from many other manufacturers. If you can untangle the rather badly drawn diagram you can see that the supply to the tap on the primary winding (which represents the 'top' of the primary winding from the point of view of the audio output valve) is smoothed only by C17, a 16μF electrolytic. The HT current to the rest of the radio passes through the remaining of the primary winding (which is acting as a choke), then R15, and is then smoothed by C16. The rest of the radio therefore gets a much smoother HT DC supply that the audio output stage.

The BC5445 I have has a rich deep sound, typical of these wooden cased radios, and there's no sign of any mains hum on the audio output, so the arrangement seems to work well. The data sheet for this radio shows the resistance for the whole primary winding (at 460Ω) and does not show a breakdown (maybe the wrong word to use) for the transformer and choke sections.

Looking at a number of GEC table models, this arrangement was pretty common (but by no means universal as there are many models which have separate smoothing chokes) and the ratings of this transformer seems to be different from model to model, even if the same output valve (the N78 was typical for several years) was used. Since these radios are not greatly collected, and therefore not highly priced, it might be worth trying to pick up a couple of scrap chassis to keep in case you have a more valued model go wrong. You can at least try a non-exact replacement to see how well it works, or split the functions into separate parts, maybe hiding the new components beneath the chassis.

Conclusions

As I'm sure anyone who has been involved in transformer design or testing would have told me, they are rather more complex animals that I originally imagined, and I have to admit to going rather further than I first anticipated when starting this article. Because the behaviour of a transformer depends on the interaction of electrical and magnetic fields with iron and air across a wide frequency range there's a lot more going on (and potentially more to go wrong) than the unwary (like me) would first expect.

Even an apparently simple concept such as the turns ratio of the windings turned out to be trickier to measure than I expected. Surprisingly I found that this ratio, which I had expected to be a constant number, 'varies' depending on how you measure it. Obviously the actual number of turns of wire on the primary and secondary isn't changing, but I clearly got different results depending on how I measured it, particularly on the frequency at which I made the test.

Using a simple test set-up, it's fairly easy to measure the 'effective' turns ratio at 50Hz, and for better quality transformers this was found to be accurate to within a few percent of the same measurement made at 400Hz. Although 400Hz is closer to the true operating conditions of the transformer, it is a more difficult measurement to make, because you need a source of AC at 400Hz. With smaller transformers the effective turns ratio at 50Hz was about 10% higher than at 400Hz, indicating a drop off in performance of the transformer at the lower frequency. It is therefore recommended that if the 50Hz value is measured, you simply add on 10% to this value to give the 'true' turns ratio.

When it came to measuring the inductance of the primary winding of a transformer, although modern (and not so modern) methods were relatively easy to use, four different methods gave four different answers. This can be explained partly by the fact that the measurements were made at different frequencies, which is unavoidable because the two LCR measuring instruments 'choose' the frequency at which the measurement is made outside the control of the user, and the other two measurements were made at either 50Hz or the resonant frequency of the inductor connected in parallel with a capacitor. For the investment of about £15 you can now buy a good quality digital LCR meter, which will be a useful companion to your standard DMM.

The fact that audio output transformers work, and work well in most valve radios and amplifiers, is a tribute to the theoretical and practical skills of the unsung engineers who designed them all those years ago. I'm sure at the time it was the RF designers who were seen as the innovators and the design of something as 'simple' as an output transformer was left to the 'less skilled' designers.

Hopefully this article will help in choosing the right transformer for a valve output stage. I suspect that most output stages are pretty tolerant to the exact specification of the output transformer and so if you can't make the tests described above, just choose a replacement about the same size as the original and give it a go!

I hope the article will also inspire you to investigate the properties of these deceptively simple looking components a little more, which I think will turn out to be more complex and intriguing than expected.

References

Reference 1: 'Practical Handbook of Valve Radio Repair' by Chas E Miller. Published by Newnes Technical Books in 1982. Contains a useful section on trouble-shooting and repair of audio frequency amplifier and output stages. Also lists a large number of audio output valves with their electrical parameters.

Reference 2: Some useful notes on valve audio output stages, and what can go wrong with them, can be found at: www.vintage-radio.com/repair-restore-information/valve_output-stages.html

Reference 3: Radio service data DVD-ROM. www.service-data.com/.

Reference 4: Tube Data Sheet Locator: http://tdsl.duncanamps.com/tubesearch.php.

Reference 5: National Valve Museum at www.r-type.org/static/museum.htm.

Reference 6: University of Pennsylvania, Department of Electrical and Systems Engineering: Transformer Lab. www.seas.upenn.edu/~ese206/labs/Transformer/TransformerLab05.pdf.

Reference 7: Linear Technology's LTspice IV software download site: www.linear.com/designtools/software/ltspice.jsp.

Reference 8: 'A Simple Procedure for Measuring Inductance' by Guillermo Rico. See: http://technologyinterface.nmsu.edu/fall96/electronics/induct/induct.html.

Here are some other references on valve audio amplifiers, transformer matching, loudspeakers and measuring inductance. If you have the magazines or books mentioned, it may be worth digging them out and taking a look.

'Radio Coil and Transformer Manual' by 'Radiotrician'. Published by Bernards (Publishers) Ltd, 1944.

'Coil Design and Construction' by B B Babani. Various editions published by Bernard Babani Ltd. Includes chapters on Output Transformers for Single Valve; Air Gap Determination; Push-pull Output and Loudspeaker Transformers; and others. Overall I found the book to be less useful than I expected, but it's probably still worth the £6 or so you should expect to pay second hand.

'Choosing an Output Transformer' by Eric Lowdon. Radio Constructor September 1951. A brief, but useful, article covering the basics of output transformer operation.

'Finding Transformer Connections' by F G Rayer. Practical Wireless August 1956. Covers mainly mains transformers, but also suggests useful techniques for output transformers.

'A Transformer for a Single-Ended Output Stage' by N P Fish. Practical Wireless February 1957. Discusses in detail the design and construction of an output transformer, and is a useful source of the rules governing the magnetic properties of the core.

'A CRL Bridge' by J Hillman. Practical Wireless January 1958. Shows the design and construction of a valve-based CRL bridge, including a 'magic eye' balance indicator.

'Loudspeaker Matching' by K Royal. Practical Wireless January 1959. Discusses impedance transformation and measuring turns ratio, and also covers driving multiple loudspeakers in series and parallel.

'An Inductance Measuring Instrument' by D Saull. Practical Wireless March 1960. Describes a simple method of measuring inductance which allows a DC bias to be applied to the inductor under test.

'Audio Transformer Design' by D Saull. Practical Wireless July 1960. Covers the design of transformers for mainly class 'A' transistor output stages, but has some information relevant to valve output stages.

'Selecting Output Transformers' by J Gray. Practical Wireless November 1960. Discusses impedance matching and calculating the turns ratio in single-ended and push-pull output stages.

'About Loudspeakers' by P J Good. Practical Wireless October 1961. Covers some of the things that go wrong with loudspeakers and tests that can be performed on output transformers.

'How to Measure Inductances' by S Jacob. Practical Wireless December 1961. Shows a simple method of measuring the inductance of AF and RF inductors.

'The Multitest' by R D Owen. Practical Wireless August 1966. Describes a comprehensive analogue multimeter and LCR bridge, capable of measuring inductance up to 4000H at 50Hz or 1000Hz.

'Understanding Radio: Parallel and Push-Pull Output Valves' by W G Morley. Radio Constructor July 1967. Contains a useful discussion of transformer air-gaps and laminations.

'Build Your Own Audio Valve Amplifiers' by Rainer zur Linde. Published by Elektor Electronics (Publishing) 1997. Contains many useful chapters on valve audio amplifiers, but surprisingly little information on the design and choice of the output transformer.

'Valve and Transistor Audio Amplifiers' by John Linsley Hood. Published by Newnes of Oxford, 1997. Contains many useful chapters on valve and transistor audio amplifiers, including discussions on the design and effect on overall performance of the output transformer in valve amplifiers.

Other sources of valve data:
'Radio Valve and Transistor Data' by A M Ball. Various editions, Published by Iliffe.

All 'valve era' editions of the ARRL Handbook had a useful valve reference data section at the back.

There are many editions of the Mullard Technical Handbook around which contain useful valve data.