Output Transformer Design and Winding

You can jump down to here to see how you might reverse engineer an output transformer nondestructively!

Or just read on here to see some of the start of the design procedure.

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3. Write down requirements
4. Select a core size
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6. Compute secondary turns
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8. Compute leakage inductance
9. If Fh is OK, go build it.
10. Otherwise, select a new interleave and go back to fitting wire.
11. Obtain materials
12. Wind the coils
13. Stack the laminations
14. Test the performance
15. If result is OK, you're done, enjoy.
16. Otherwise, go back and select a new (probably bigger) core size and loop back through the process.

Understand the terminlogy

E-I lamination	A flat transformer steel lamination composed of pairs of E-shaped and I shaped pieces. The middle projection or tongue of the E is placed through the center of a coil of wire, and the I placed at the end like this" EI" so the iron forms a complete magnetic path through the center and around the outside of the coil.
Scrapless lamination	An E-I lamination with proportions such that two E's and two I's are stamped from a rectangle of iron with no waste left over. This is the least expensive shape for transformer iron, and is the standard for the industry for non-special purpose transformers. The proportions are special, obviously. The I's are stamped from

	the open areas of two end-facing E's. The middle part, or tongue, of each E is twice as wide as the two outer legs, and the empty area stamped out of the E (which forms the I) is half as long as the E is high from top to bottom. As you can see, since the proportions are pre-determined, you can specify any one dimension and all the rest are determined. E-I laminations are usually named by the tongue width: EI100 has a tongue that is 1.00 inches wide. EI150 is 1.5" wide, etc.
primary inductance	If you connect only the primary wires of a transformer, and measure the inductance, no energy leaves through any secondary windings, so the thing looks like (and is!) just an inductor. The amount of inductance you measure is the primary inductance. The primary inductance is a consequence of the iron and air in the magnetic field path, and is non-linear - you would measure somewhat different values under different conditions.
secondary inductance	Likewise, what you measure if you connect a measurement instrument only to the secondaries.
leakage inductance	Leakage inductance is inductance that results from the parts of the primary's magnetic field that does not link the secondary. This is an inductance from which the secondary can never draw energy, and represents a loss of effectiveness in the transformer. If you short the secondary winding and then measure the "primary" inductance, you will measure the leakage inductance, which appears to be in series with the primary winding.
core loss	The iron in the core is itself conductive, and the magnetic field in it induces currents. These currents cause the loss of energy, and this comes out as heat. The core loss represents a price you have to pay to use a transformer. Core loss is strongly related to frequency, increasing linearly as the frequency goes up.
eddy current	Eddy currents are the currents induced in conductors in a magnetic field - such as the iron core. The inside of a conductor looks like a shorted transformer turn to the magnetic field, so the currents can be large, and can cause substantial heating, as in the core losses.
copper loss	Copper is not a perfect conductor. Current moving through copper causes the copper to heat up as it moves through the resistance of the wire.
winding window	This is the area of a core available for winding wires into.
margins	Space left at the end of a coil former where no copper windings are placed. This keeps the copper wire from going out to the very edges of the coil former, and improves the voltage isolation between layers and windings.
window fill	The amount of the winding window that is filled up with copper wires, insulation, etc. Usually expressed as a percent of the winding window area.
interlayer insulation	After winding a neat layer of wire on a coil, you put a thin layer of insulating paper, plastic film, etc. over it. This is interlayer insulation. It helps keep the insulation of the wires from breaking down from the stress of the voltage difference between layers, and mechanically helps form a neat, solid coil.
B	Magnetic field intensity, or "flux density"; sometimes measured in flux lines, Gauss or kiloGauss, or Teslas depending on the measurement system you use. Most transformer iron saturates around 14 to 20 kGauss. Ceramic materials saturate at around 3-4kGauss.

H	Coercive force. This is what "forces" the magnetic field into being. It's usually measured in Ampere-Turns per unit of magnetic circuit length, often ampere-turns per meter.
B-H curve	Pretty simply, the graph of B versus the causative H. When there is a large slope of B versus H, the permeability of the material is high.
saturation	At saturation, the permeability falls off, as more H cannot cause higher B.
Insulation class	Transformer insulation is rated for certain amounts of temperature rise. Materials which withstand temperatures under 105C are Class A. Class B materials withstand higher termperatures, and other letters even higher temperatures. Class A insulation is the most common for output transformers, as no great temperature rise (by power transformer standards at least) are encountered. This "class" is not related to the bias class of the amplifier at all, they just happened to use the same words.
Stack	How much iron is put inside the coils of wire making up the windings of the transformer. The lamination size determines the width of the tongue, the stack height determines the height, and the width times the height is the core area, which is a key determiner of the power handling capability of the transformer. All other things being equal, more stack height means either a greater inductance for a given number of turns, or a fewer number of turns for the same inductance. This is one means of juggling wire sizes and window fill.

Understand the transformer equivalent circuit

Write down requirements:

Determine:
Power through the transformer
Lowest frequency to be passed
Highest frequency to be passed
Primary and secondary voltages or impedances to be matched
Primary/secondary voltage and impedance ratios

Write down requirements:

Determine what you're going to build (or hope you are!). To do this you need a clear statement of your design goals - what you are going to build, what output tubes you will use, what impedance(s) are to be matched, etc.
As an example, you might want to design an output transformer for a single pair of 6L6 output tubes. From the tube data books, you determine that a pair of 6L6's will put 40-50W in Class AB push pull into a 4400 ohm plate to plate impedance. You know you would like to match this impedance to loads of 8 and 4 ohms, and this will be used for guitar only, not bass or hi-fi.
By merely stating that, you have defined a lot of what you need to design a transformer. The power requirement and the low frequency requirement effectively set the physical size of the transformer, and the high frequency limits implied in the "guitar" frequency range sets a minimum upper bound on the high frequency response of the transformer, and hence an upper bound on the leakage inductance that the transformer can have. The choice of biasing into class AB is also significant, as this helps define the current range in

the primary winding and sets a lower limit on the size of the wire the primary can be wound from.
Determine:
Power through the transformer = 50W (estimated)
Lowest frequency to be passed = 82Hz
Highest frequency to be passed = 10KHz
Primary and secondary voltages or impedances to be matched: Xp=4400 Xs=8, 4 ohms
Primary/secondary voltage and impedance ratios: Xp/Xs= 4400/8=550 4400/4=1100.
Ns/Np=23.45 and 33.2 (4 ohms)

Select a core size for the given power level:

This is best done by experience- e.g. other designs, or relating to a 60Hz power transformer of known power. However, you can also do it by computing the area product of laminations and estimating. If you're serious about this, consult Flanagan's transformer design books for charts and graphs or other transformer references. Experience or comparison works best, though, and is what the pros do in practice.
There are a number of factors in transformer design that influence the size of the core and hence set the size in one way or another. These things are related to the more normal things we look at and measure by some pretty complicated math and/or modeling relationships, and so they are essentially not calculable by the average Joe Designer. Even experienced designers use tables, charts, and the seats of their pants to pick a core.
If you have a replacement application in mind, a really, really good guess is the size that is in there now, plus a bit if you want to make it better some way. The simplest way to allow for extra goodness to be poured in is to make the "better" replacement somewhat bigger.
Usually, since a transformer's cost of manufacture is about 80% based on the cost of the iron and copper in it and relatively little on the labor content, the economies that limited the original in some way were oriented toward making the final result the smallest and lightest it can be made - least iron and copper. Not being under such a restriction, you are free to make it better and remove some restrictions on you and your design by using a slightly bigger core.
Since the area product (winding window area times core stack tongue area) determines a lot of things about a transformer, you'll want to enlarge that by either using a bigger stack of laminations (which increases only the core area) or by going to a bigger lamination, which increases the winding window and potentially the core area as well.
For a number of practical winding reasons, you should stay with a core stack between square (the stack is the same height as the lamination tongue is wide) and a stack twice as high as the tongue width. Using a bigger lamination and a stack smaller than square is usually not an economical success. If you need to go bigger than a 2:1 stack, then go to the next bigger size lamination and a stack that may be a trifle less than square if you have to.
Since a power transformer can be thought of as an audio transformer that only has one frequency in it, you can use the size of a 60Hz power transformer of known power as a reference for an output transformer for guitar. If you assume that the power transformer is probably designed a bit too close to the saturation flux density than you want, but that your lowest frequency is 82 Hz, not 60Hz, these two offer a first order offset, and for a

50W 82Hz output transformer, a 50W 60Hz power transformer would be close to the same size; certainly a good starting point. If you're trying to design a bass output transformer, that's an octave down from guitar, and you'd expect that it would be about twice as heavy since the lowest frequency is half that of one for guitar, so a good starting point for estimating the size of a bass transformer would be a 60Hz power transformer of about 100W rating. Note that transformers are rated in VA (Volt Amperes), which is like watts, but includes the possibility that the load is reactive and what it passes may not be real watts, but the volts will be the same and the total number of amperes will be the same.

As I mentioned, there is a pure computation method that can be done by computing the area product of laminations and estimating the power capability of the iron stack from that, but it is involved, and you'll have to dig it out on your own. I don't want to type the several pages that are needed. There's a useful quote in the Radiotron Designer's Handbook, 4th edition:

"As a general rule, the output transformer should have the largest core which is practicable or permissible having regard to cost or other factors. A large core of ordinary silicon steel laminations is usually better than a small core of special low-loss steel."

When in doubt, make it bigger.

Compute turns

Compute Lp= Xp at Fl
Compute Np from Lp for the given core
Compute Np for Bmax<core material requirements
Use highest Np
Compute Secondary turns from Ns/Np or Xs/Xp

Compute turns

To determine the number of primary turns needed, you will have to satisfy two constraints. First, the primary inductance must be large enough to not shunt the power from the output devices away from the reflected load. This has the effect of requiring that Xlp be from equal to the plate to plate load at the lowest frequency of interest (which implies a 3db or half power loss) to being larger or much larger than the plate to plate load. As an example, if you want a 4400 ohm plate to plate load down to 82Hz, the minimum primary inductance you should use will be Lp = 4400/(2*pi*82) = 8.5 Hy. That will mean that you will have out only half power at the lowest notes of a guitar. If you want better response, you might want to up that by double, or quadruple. Assume you want to double it to 17 Hy. From that inductance, you can compute the number of primary turns to get about that inductance from your target core and stack.

In an actual design, you probably want the response to be not more than 1db down at the lowest note, not 3db down as the normal engineering calculations would suggest. That indicates making the primary inductance even bigger.

A word about inductance. Primary inductance is NOT a constant. It varies with the care of stacking and adjusting the laminations, with the amount of excitation of the windings, and with any DC current through the windings. Compute a good target primary inductance, but don't get too excited if you don't get really close to the target.

Computing the turns needed for a certain minimum inductance can be done two ways. One is an analytical way, using the permeability of the laminations you'll use.
By that method, N= Sqrt((Lp*l*10**8)/(3.2*A*u))
Where Lp = desired primary inductance
l = magnetic path length for the lamination in inches
A= core stack area, square inches
u= permeability of the core material
The manufacturer will of course have to supply you the number for permeability, or you'll have to measure it - a tough task. Lamination makers usually don't supply that number. What they do is to tell you the inductance of a square stack with 1000 turns of wire on it. Since inductance is linear with core area, and turns squared, you can compute turns for a given inductance directly from the maker's supplied inductance constant.
The reverse is also true. You can take your preferred lamination, make a square stack with a nominal number of turns (1000 is a lot of work, but gives good measurements) and determine the inductance for that winding. This will also subsume your stacking and adjustment skills, and will be a more accurate number for how *you* will wind the transformer.
Once you have done that, you also need to compute an independent number of primary turns to keep the core from saturating on peaks of input signals at the lowest frequencies. Here, you pick a nominal saturation flux density for the core material (usually 14kGauss for silicon steel transformer laminations).
Obviously, you'll need to know the peak signal level, and the lowest frequency. Again, for guitar, the lowest frequency is 82 Hz, and 41 Hz for bass. The peak-to-peak signal voltage can be taken to be the B+ voltage minus about 50V saturation on the output tubes. Assuming that this is a square wave is conservative; assuming a sine wave will lead to saturation in some cases - but you might want that, so think about it. For example, a 450V B+ gives a 400V pk-pk AC wave, which would be a 200Vrms square wave, or a 142Vrms sine wave.
Compute the number of primary turns that will keep that voltage from saturating the iron at that lowest frequency by computing
N = (E*10**8)/(kfbA)
Where E= Applied AC signal voltage
k= 3.5 to 4.44, depending on stacking factor. 4 is a good starting place for hand stacking. This parameter is often taken to be 4.44 for sine wave excitation and presumed perfect stacking. Be conservative.
f = lowest signal frequency
b = max flux density, somewhere between 10kG (well designed, low distortion hifi output transformers) and 17kG (power transformers); 14kG is a good start for guitar amps
A = area of the stacked tongue, square inches.
This is one place that the art of transformer design comes in. It turns out that the peak flux density in the iron can be directly related to the amount of distortion that the transformer will cause - the lower, the better. If you choose to go for a much lower distortion, you must limit the flux density by using even more turns. This may cause you to have to use finer wire, which may cause too much copper loss, or it may force you to a bigger core size. Usually, it is not necessary to keep flux density under 10kGauss even in

hi-fi output transformers if you're using 4% silicon steel (the most common transformer iron).
Once you have two primary turns calculated, you pick the larger of the two as the number of primary turns. It usually works out that the number of turns you calculate for the desired primary inductance will be larger than the number you calculate to keep the flux density down to some specific level, but not always.
Compute Secondary turns from Ns/Np or Xs/Xp

Fit wire to core window

85% target window fills
Even layers, margins, spiral windings, etc.
Interlayer and interwinding insulation.
Choose wire sizes, etc.
From our earlier calculations, we know how many turns have to fit in. It remains to pick which wire sizes to wind. It is very difficult to actually fill up more than about 85% of the winding window in E-I laminations, so we use 85% as a starting target.
The primary has to carry the whole power output plus losses, so we start by assigning it about half the available area, or 42.5% of the window. The secondaries will get the same. From there, we can divide the number of turns by the area to get the number of turns per square inch for the given wire, and consult a wire table for the nearest smaller wire size. This is the biggest practical wire size that will fit in the allotted window area to a first approximation. We also can calculate the wire size based on the currents. Wire tables list the size of the wire in "circular mils". If we assign a reasonable value of area per current, that is another way of finding a starting wire size. By experience, conservatively rated transformers usually work the copper wire at about 750 circular mils per ampere, and more-stressful use is something like 1000 circular mils per ampere. If you know the current, you can simply divide the current into the listed circular mils for wire and then p! ! ick the wire size that gives you closest to the working current density you want. This wire size is likely to be smaller than the size picked by the "maximum area" method. If it's bigger, you either have to work the wire with higher current density (more copper loss, higher temperatures) or go to a bigger core that lets you have more window area. In most cases, the max area wire size will give you an upper bound and the current density a softly defined lower bound on the wire size. You have to repeat this set of calculations for each secondary.
Once you settle on wire sizes, you have to compute the actual fit. The wiring should come out not only in about the right window space, but in even layers on the coil former. Using the wire tables, compute the number of turns per layer (being sure to use the diameter of the wire WITH insulation), leaving a margin at the end of the coil former of about 1/16" to 1/8" depending on wire sizes, with the bigger wires having the bigger margins. Once you know turns per layer, you can find the number of layers.
When you have wire sizes, layers, margins, etc., you can compute the build up of wire over the coil former, including wire, insulation, interlayer insulation, and all. This must come in less than the window height, or you have to start over with a bigger window (by using a bigger lamination), fewer turns by using a larger stack of iron, or smaller wire and higher copper loss.
Two or three passes through this will get you a fit on wire size in the window.

Compute leakage inductance for primary over secondary.

Compute Fh from "basic Leakage"
Select a new interleave factor based on Fh and Ll.
With a basic buildup of wire in a window, you can calculate the leakage inductances. For a simple primary-over-secondary winding, you can calculate the leakage reasonably well by knowing the physical dimensions of the window, and windings in the window. From there, the leakage inductance is reduced by the square of the number of interleavings. When you pick a new interleaving you must do the same construction of windings and build up you did with the initial wire sizes to check the fit in the window.

Obtain Materials

This is tough. Small orders to lamination makers are likely to difficult. You might try unstacking and unwinding a suitably sized 60Hz power transformer if the iron laminations are thin enough. (Note - good audio transformers have historically used iron of about 0.014" thickness, about twice the thickness of a computer card - which is itself becoming almost unknown.) Unwinding one is also one of the best introductions to transformer winding technique that you can get. Unwind one with the objective that you could put it back together if you wanted to. When you get done unwinding, you'll be semi-educated about how the winding should be done.

Wind the coils

Stack the laminations

Test performance

Reverse Engineering an Output Transformer - Nondestructively!

This question popped up at Ampage, and it needs a long answer, so I'm going to type it in here.

What simple tests can be done to capture the specs of a vintage output transformer? You may not be able to fully blueprint the iron through any simple calculation, but you might be able to then provide some spec to produce another?

Fortunately, you can discover almost everything you need through nondestructive tests. We'll assume you have a working transformer running properly in the circuit it was designed for. This won't be trivial, but it's well within the reach of a modestly-equipped ham radio operator or well equipped amp tech.
In-circuit tests
With the transformer in the circuit, run the circuit at full non-distorted power (no visible sine wave distortion) and measure the AC voltages on each winding. With no signal in the circuit, measure the DC voltages at each point on the primary.
Designed Volts/turn constant
Remove the transformer from the circuit. Using a ball-point carpet needle, thread some fine magnet wire through the spaces and holes between the core and windings. This does

not have to be neat, you just need to get the turns in there. Count the turns *accurately* as you put them. 10 is probably enough.

Drive the transformer secondary with a non-distorted sine wave of a few volts and 400 to 1000Hz through the transformer. Accurately measure the voltage on the secondary and on your added 10 turns as well as the primary. Make certain that all windings except the driven secondary are open circuited, no load at all. The voltage on the 10 turn winding lets you calculate the volts per turn that the transformer is running at. From this, you can calculate the number of turns on any winding, subject only to the accuracy with which you make the measurements, by measuring the voltage ratio to the 10 turn winding and the normal winding, then multiplying by the number of turns on the test winding. Do this for all windings. Using the AC voltages you measured for normal operation, you can now calculate the maximum volts/turn for the transformer.

Voltage/turns ratios

Having measured all the voltages in normal operation, you have the turns ratios and impedance ratios too, with just calculation.

Wiring resistances

With an accurate ohmmeter, measure the DC resistances of all the windings. For windings under 100 ohms, you probably need a meter designed for measuring low ohms.

Primary inductance

Set up a test circuit with a high power transistor or MOSFET switch to switch 12VDC into the series connection of the transformer primary and an accurately known resistor to ground. Parallel the series resistor/primary with a clamp diode that is normally reverse biased. Drive the switch with a variable duty-cycle pulse generator and slowly increase the duty cycle from very tiny, watching the voltage across the resistor and inductor with an oscilloscope. The voltage across the resistor, which is proportional to the current through the inductor, will ramp up linearly when the switch is on and ramp down linearly through the diode when the switch is off. Ensure you never use a duty cycle of 50% or more, as that does not let the inductor current go to zero before it is started back up again. In this case, the inductor current will ramp into saturation and burn something out. Accurately measure the ramp time for a ramp up to some moderate current, like maybe 50-70ma. Compute the inductance from the R-L time constant. For primary inductances, ensure that all other windings are open circuited. You will find primary inductances in the range of 5-50Hy for most musical amplifier transformers. Hifi outputs may have primary inductances in the 100's of Hys.

Leakage inductance

Repeat the primary pulse inductance test, but this time short the secondary winding. The inductance will be lower by a factor of 1000 to over 100,000; the less the ratio of leakage inductance to primary inductance, the better the transformer, and the harder it is to wind.

Primary self capacitance and rimary to secondary capacitance

These are measurable, but unimportant for musical amplifier output transformer use. They won't make a difference in the design.

Core measurements

Accurately measure the size of the laminations and the depth of the stack. Use some magnification and calipers and eagle-eye the thickness of the laminations.

B-H curve
If you're dead set on duplicating the transformer, there's a test you can do. More on that one later.
Now that you have all this, what do you do with it?
If you think about it, this is pretty much the same as a new transformer design where you've already determined the number of turns and core size, which speeds things up a lot. All you have to do is fit the wire into the window by selecting wire sizes and turns per layer, and then choose the interleaving to get the leakage inductance down.
Wire fitting is easy once you've done it once, and is pure drudgery.
Interleaving is the hard part. There are whole chapters in transformer books on interleaving. The net of it is that the leakage inductance of a simple primary-over-secondary is calculable with reasonable accuracy from the physical measurements of the window and the windings. From there, the leakage inductance goes down by the square of the number of interleavings. From some simple calculations out of the wire fitting, you can estimate the leakage with no interleaving, and then make a good guess about how many interleavings to do. HOWEVER.... there is no nondestructive way to find out the interleavings the original transformer had. You can build and test until it is close, though, if you're persistent enough.