Output Transformer Design

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This article not only explains the "mystic" factors in output transformers, and tells how to design them, it makes important suggestions the author considers essential to continued progress in the industry.

THE OUTPUT TRANSFORMER is one of the more important components in any modern amplifier as regards its contribution both to cost and to performance. So the primary considerations in designing an output transformer must resolve into various aspects of the economic question, "How good, for how much?" Keeping "both feet on the ground," we will start by considering the various items that contribute to the over-all cost of an output transformer.

Costs

On the material side, there are two main groups of cost: the core and the winding. Two classes of core material enter the consideration: the fairly inexpensive silicon-iron alloys that come in stamped or punched laminations; and the much more expensive grain-oriented strip-wound material, ranking in the order of ten times the cost for the corresponding weight.

Compared to these costs the cost of winding material is relatively small. The principal economic question in relation to winding material concerns choice of the best wire *covering,* which is usually enamel, or a similar material. From the viewpoint of achieving the lowest cost, a more expensive covering is sometimes justified, because it enables the winding to be accomplished more readily without the risk of shorted turns. Associated with wire covering is the matter of a suitable impregnating compound, which can finalize the winding assembly and prevent its deteriorating due to atmospheric conditions in which the transformer will work.

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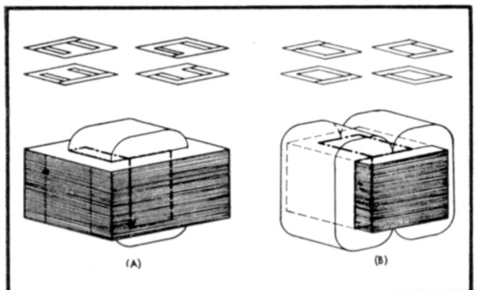


Fig. 1. The two types of construction employing punched laminations. Above each is shown, reduced in size, the lamination configuration used to build it up. At (A) the shell type, using a single coil assembly, with E and I, or T and U laminations. At (B) the core type, using two coil assemblies, with U and I, or L laminations. In each case, the heavy dashed line outlines the magnetic path area of the core, while the heavy dot-and-dash line outlines the winding window area.

On the labor side of the question there are again two major operations: the winding and the complete assembly. In determining the lowest cost for a given performance, one has to take all of these elements and see which one adds up to the lowest figure. For example, concerning the winding labor: it may be possible to save material in the core and winding, but the result of this saving will be that a more complicated method of mixing is necessary, which will put up the cost of labor for winding the coil.

Similarly with the assembly part of the story: the more expensive grain-oriented, or C-type core, does have the advantage that the assembly labor costs are reduced; with the older lamination type core, although the material is much cheaper, assembly takes longer and hence is more costly; the C-type core is very quickly and easily assembled with simple tools.

Choice of Core Type

All of these costs have to be weighed against various performance considerations that may be laid down in the transformer specifications. The first major question to decide now is the kind of core to be used: whether to employ a C-type core or one of the laminated varieties. So we will start by giving some approximate comparative figures relating the two kinds of material.

Of course, these will provide only a guide, because the final answer to the question depends upon the precise costs of labor and materials, which are factors that vary widely from place to place and over a period of time: the most economic solution at one place and time may be the least economic solution at some other place or time. The purpose here is to give some performance comparisons. Then the cost figures can be put in and the various other relevant details, to help make the decision.

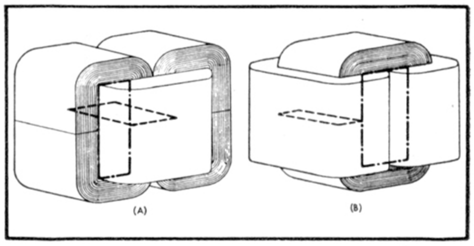


Fig. 2. The same two types of construction employing prefabricated C cores wound from grain oriented strip.

The first thing to notice is that the relative dimensions change between the two kinds of core. For a good transformer using a built up laminated core, the usual proportions constitute a larger volume of core than of winding. These laminations are relatively cheap and, even if they were a little more expensive in comparison with winding material, the large core section would still be the most economic proposition because it makes for a simpler type of winding and assembly.

Changing over to the C-type or strip-wound core, the trend is towards a much more conservative core cross section and a larger winding window. The reason for this is the very much greater relative cost of the C-core materials. By making this change, the over-all cost of a transformer with similar performance can be kept in the same region—it may be more or less according to the precise features involved and the relative cost of materials involved. However, it would become exceedingly complicated to make a direct comparison between cores of one material in one kind of proportions, and cores of a different material in different proportions. So we shall make the comparison on a step-by-step basis.

At this point however, an important point should be stressed. Recently the author encountered a case where transition from laminations to C core had been made, simply by removing the laminated

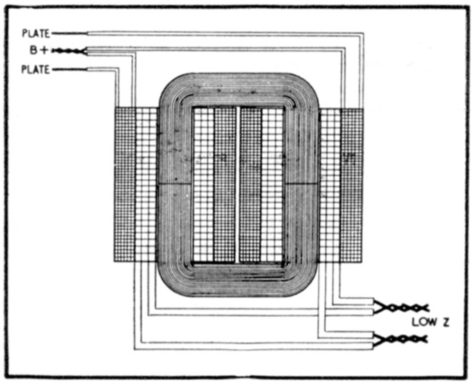


Fig. 3. Section through a transformer using a single C core, relying on electrical interconnection for low leakage: each limb of the core is virtually a separate transformer, one for each plate circuit, and the secondary low-impedance windings **must** be paralleled; to maintain high core inductance, the winding connections should be such that the core magnetizing effects are in phase.

core and inserting a pair of C cores that happened to fit conveniently over the same bobbin. *This change is never an economic proposition.* To the uninitiated, it would seem that the principal difference is a relatively large air space in the winding window of the C core, and air does not cost anything! Of course, there is a little more core material, due to the increased length necessary to "go round" the air space. But make a quick comparison this way:

With E and I laminations, the transformer had been about 94 per cent efficient; the change had improved the efficiency to about 96 per cent and increased the power at the low end about three times. But had the coil been redesigned and rewound to fill out the same pair of C cores, the efficiency would have jumped to almost 99 per cent and the low-frequency power rating about eight or ten times.

This improvement is probably much more than the customer needed. So a smaller C core could have been used for the design. That change raised the cost from $14 to $16. In all probability a change tailored to suit the customer's needs would cost not more than the original transformer. This brings us to the first basis for comparison.

Power Rating and Efficiency

First we assume that the build-up of the strip-wound C core is such as to produce a transformer identical in dimensions with one using a laminated core. Under these conditions, using the same winding, that is, number of turns and wire gauge, the working impedance of the winding for maximum energy transfer efficiency can be pushed up by a ratio approximately 1.55. This is because of the very much reduced shunt losses in the core.

This change in working impedance means that the losses will be reduced in this same ratio. If the laminated core produced a transformer of 90 per cent efficiency (i.e. 10 per cent losses), the C core using identical dimensions would produce a transformer of 93.5 per cent efficiency (i.e. 10 per cent ÷ 1.55 losses). However if both types work at maximum energy transfer efficiency, in all probability, due to the change in relative dimensions, the full advantage of this improved efficiency will not be gained. On the other hand, the laminated type core often does not work at optimum efficiency due to other considerations, so it may be that the C core will gain an even greater improvement in power transfer efficiency.

Taking an alternative assumption—that we will be content with the same efficiency in the two kinds of transformer (of the same size and shape)—the power rating can be pushed up at the low-frequency end due to the reduction of losses and the change in nominal impedance that can be achieved for a given winding. Due to reduced losses, the working impedance of a given winding can also be reduced by a factor of 1.5 for the same efficiency, so the power rating can be increased by a ratio of 1.5. Further than this, due to the increased permissible flux density before saturation is reached, the power rating can be increased approximately 7 times.

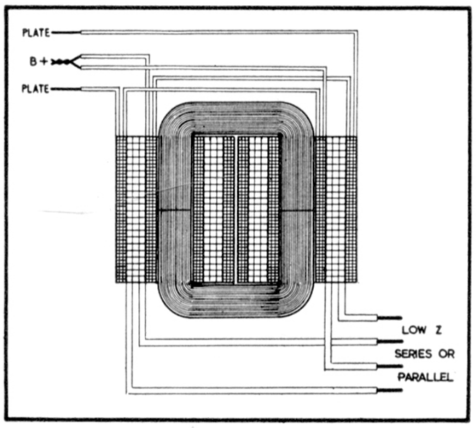


Fig. 4. Section through a C core transformer relying on distributed transformer action for low leakage: each limb carries half of each plate winding and half of the secondary; as a result there is no leakage flux potential between limbs, and the windings may be connected in series or in parallel to suit impedance requirements.

Thus the over-all increase in power rating for a given size of transformer can be more than 10 times. This means that, if the transformer using regular laminations gives maximum power down to a frequency of 60 cps, one using the C-core construction would give ten times the power at 60 cps, or approximately the same amount of power down to 20 cps.

Frequency Response

The figures just given relating to maximum power at the low-frequency end are not *directly* related to the matter of frequency response—a fact that often does not seem to be appreciated. Maximum power at the low-frequency end is controlled by saturation flux density, whereas the *response* at the low-frequency end is controlled by the effective inductance produced by the core *below* saturation flux density, using the same winding as a reference.

A comparison between the C-core materials and the older lamination type materials, shows that the effective permeability below saturation is increased by an average figure of 3.5 times. This means that the primary inductance of a given winding, on a core of the same proportions, would be increased by 3.5 times. As the operating impedance of this winding will probably be increased also, this means that some of the benefit will be transferred to the upper end by reducing the leakage inductance referred to the specific impedance used.

The exact distribution of the improvement in frequency response will depend upon the relative distribution of other losses. The best way to express

SIZE DESIGNATION	MATERIAL	QUANTITIES REFERRED TO 1000-TURN WINDING OCCUPYING HALF OF AVAILABLE SPACE							MAX. POWER 60 cps	ROLLOFF	
		Winding Resistance (total referred)	Core Losses (K)		Minimum Inductance	Leakage Inductance	Maximum Efficiency	Optimum Impedance		LOW	HIGH
			R_e	R_{h60}	Hys.	mH	%	ohms	W	cps	cps
EI-12 × 1½"	High Silicon	70	120	20	35	30	95.2	2900	7.5	18	15,000
EI-12 × 3"	"	100	240	40	70	43	95.9	4900	15	12	18,000
EI-13 × 2"	"	28	160	27	47	50	97.3	2100	25	8.5	6,800
EI-13 × 4"	"	39	320	54	94	70	97.7	3500	60	6	8,000
50/18/13	C-core	17	190	28	70	40	98	1800	65	4	7,000
50/32/13	"	21	340	50	125	49	98.4	2700	135	3.5	9,000

Fig. 5. Method of tabulating data to facilitate output transformer design. Optimum impedance is that for maximum efficiency. Maximum power and the frequency response roll-offs are based on the optimum impedance given. Power rating can be increased, and low-frequency response extended, by using an impedance lower than optimum (or more turns for a given impedance). In the opposite direction, high frequency response can be extended by using an impedance higher than optimum (or less turns for a given impedance). Where requirements conflict, high-frequency response can alternatively be extended by sectionalizing.

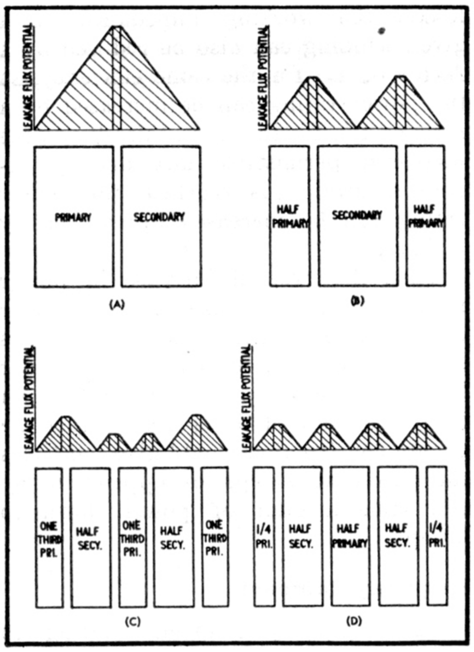


Fig. 6. How sectionalizing influences leakage inductance. The significance of leakage flux potential, and the relative advantage of the arrangements shown, are discussed in the text.

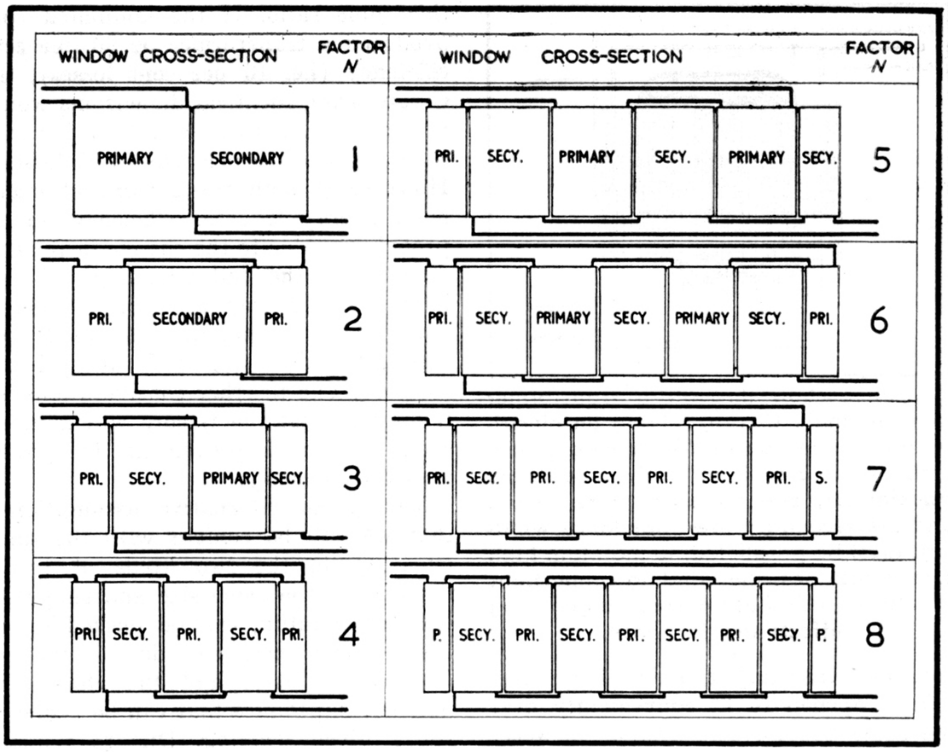


Fig. 7. Table of sectionalizing arrangements with the values of factor N to be used with the chart of Fig. 9 in computing leakage inductance.

the matter is that the over-all frequency response will cover a band width increased in *ratio* by approximately 3.5 times, using a coil and core of the same dimensions and proportions.

In practice, as the C-core construction employs a relatively larger window for the size of the transformer, it is easier to employ a greater amount of mixing in the construction of the winding. Also as the core is more costly it is more economic to spend a little more on winding than to go to a larger core size to achieve a given improvement.

The net result, then, is that change from the old laminated core to the newer C-type cores promises an improvement in frequency response band of *at least* a ratio of 3.5.

Size and Weight

For some applications the big problem is size and weight: how small can we make an amplifier to deliver a given power? The easiest way to arrive at a comparison on this basis is to consider how the relevant quantities vary as size is changed, maintaining the same shape. Under this condition, the same number of turns will represent the same operating impedance, for maximum energy transfer efficiency, and both core losses and winding resistance will vary directly in inverse proportion to the linear dimensions.

This means that, when energy transfer efficiency is the controlling factor and, due to the change in material, we have reduced the losses by a ratio of 1.55 for the same size, we can in turn reduce the size, to bring the losses back to the original figure, in linear dimensions by a factor of 1.55. This represents a reduction in weight or volume to less than 1/3 of the previous value—not much more than ¼.

It may be that the limiting factor is the power handling capacity at the low-frequency end, in which case the power handling capacity of a given number of turns on a particular core *shape* will vary approximately as the fourth power of the linear dimension. As for a given size, we had an improvement of 10 times, this means that linear dimension can be reduced by the fourth root of 10, or the volume and weight by the ¾ power of 10. This represents a possibility in size and weight reduction of better than 5 to 1 by using the C-core material.

As this shows a better reduction than the one based on consideration of energy transfer efficiency, it means that the efficiency will be probably somewhat reduced by using this greater reduction.

To get some kind of cost comparison we need to have a means of considering how change in the relative quantities of core and winding volume will affect the situation. As a general principle we can make the assumption that a constant performance can be achieved by having a constant *product* of core and winding volume. This means that if we halve the core volume we need to double the winding volume to maintain a compatible performance. This is approximately a sound foundation for comparison, but of course there are many other factors that must be considered in completing out a design.

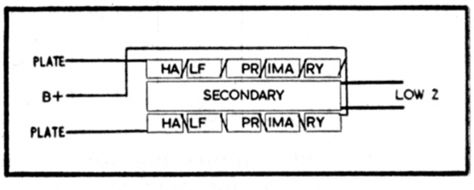


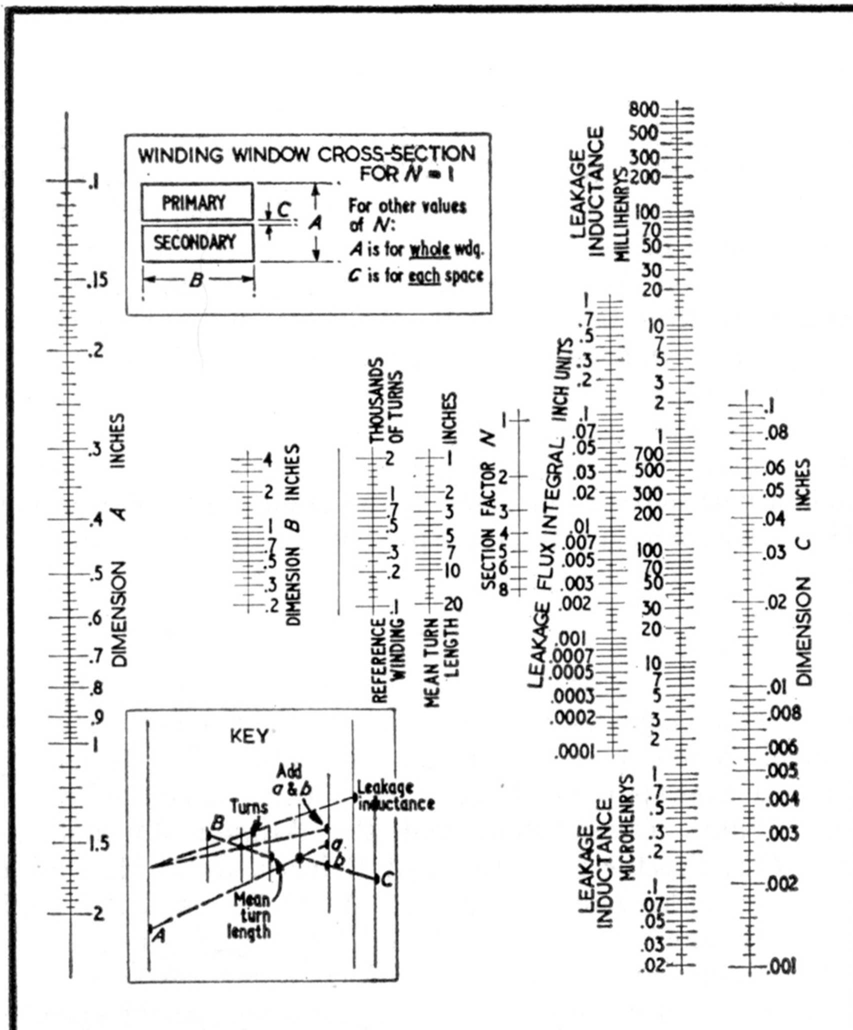
Fig. 8. A cross section through a simple winding arrangement where both leakage inductance and primary capacitance have to be minimized. This is only likely to be required with the higher plate circuit impedance values.

Using this as a basis of pricing both kinds of transformer in *dollars per pound,* exclusive of case, impregnation, or filling, we find that the C-core variety shows an increase over the old laminated type in the region of twice. This means that if we utilize a C-core construction of approximately half the total volume of the previous laminated core construction, we shall land up with a transformer of approximately the same price.

The foregoing discussion has shown that, whichever criterion is considered as a basis for performance comparison, a transformer of half the volume on C-core construction should achieve better performance than its prototype in the laminated core construction.

Choice of Core Size

Closely associated with deciding what material the core should be made of, comes the question of the size and shape. Laminated cores are built up, from stampings of specific dimensions, to a desired stack thickness as shown at *Fig.* 1. There are two basic shapes, one of which may be built up with laminations of E and I, or T and U configuration,



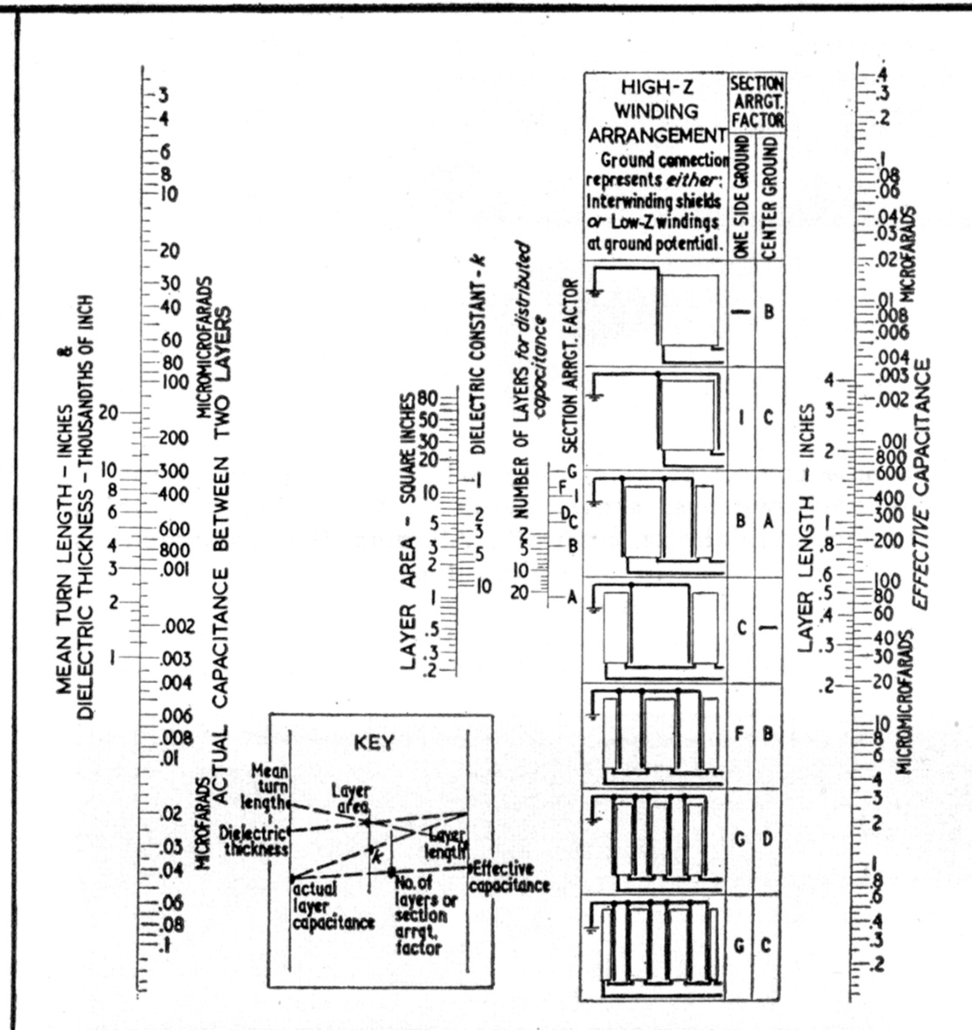


Fig. 9. (left). Chart for the computation of leakage inductance. The section factor for any given arrangement of winding cross section can be obtained from Fig. 7. Fig. 10. (right). Chart for the computation of various winding capacitances. The value of dielectric constant **k** used must take into account the material used to provide interlayer or interwinding insulation, and also the effect of impregnation if employed. The number-of-layers scale is used for finding the effective terminal capacitance due to distributed interlayer capacitance. The section factors, obtained from the table inset, are used to find the total terminal capacitance due to spaces between the high-impedance winding and either shields or low-impedance winding sections, as shown in the table.

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it is advantageous to tabulate information so that the power rating and other data about given core sizes may be seen at a glance, enabling suitable designs to be considerably expedited. Such a tabulation is illustrated at *Fig.* 5.

For a relatively simple and inexpensive amplifier a simple design of transformer with a minimum of mixing between the windings will prove adequate but for really high quality amplifiers with wide-band frequency response between close limits, a larger amount of sectionalizing and mixing becomes necessary. However, it is not profitable to just keep on dividing each winding into a greater number of sections indiscriminately. There are economic and uneconomic ways of sectionalizing, according to the purpose for which the sectionalizing is required.

It should go with saying that dividing the winding into sections will not effect any improvement at the low-frequency end. Primary inductance and saturation density are purely a matter of core dimensions and the number of turns provided on the windings. It is immaterial at these frequencies how the turns are arranged, so sectionalizing is only of importance at the high-frequency end.

But there are two ways in which sectionalizing can affect the electrical properties of the transformer. These are to reduce the winding capacitance and leakage inductance respectively. In earlier days, when tube load impedances tended to be much higher than the modern values, winding capacitance could be quite a problem. It can still be a considerable problem in drive and interstage transformers, but for output transformers it does not usually prove to be too serious a problem.

The major purpose of sectionalizing in an output transformer is usually to reduce leakage inductance. The extent to which either of these components requires to be reduced depends somewhat on the purpose for which the amplifier is required. If the amplifier is for laboratory purposes and will work into a resistance load primarily, then both leakage inductance and winding capacitance share an important relationship which must be considered in detail.

For the more common condition where the amplifier is intended to feed a loudspeaker load, the leakage inductance will usually be swamped by the voice-coil inductance of the loudspeaker which the amplifier feeds. However, if feedback is taken from the secondary of the transformer to some earlier stage in the amplifier, the leakage inductance comes within the feedback loop and hence must be considered in the over-all design.

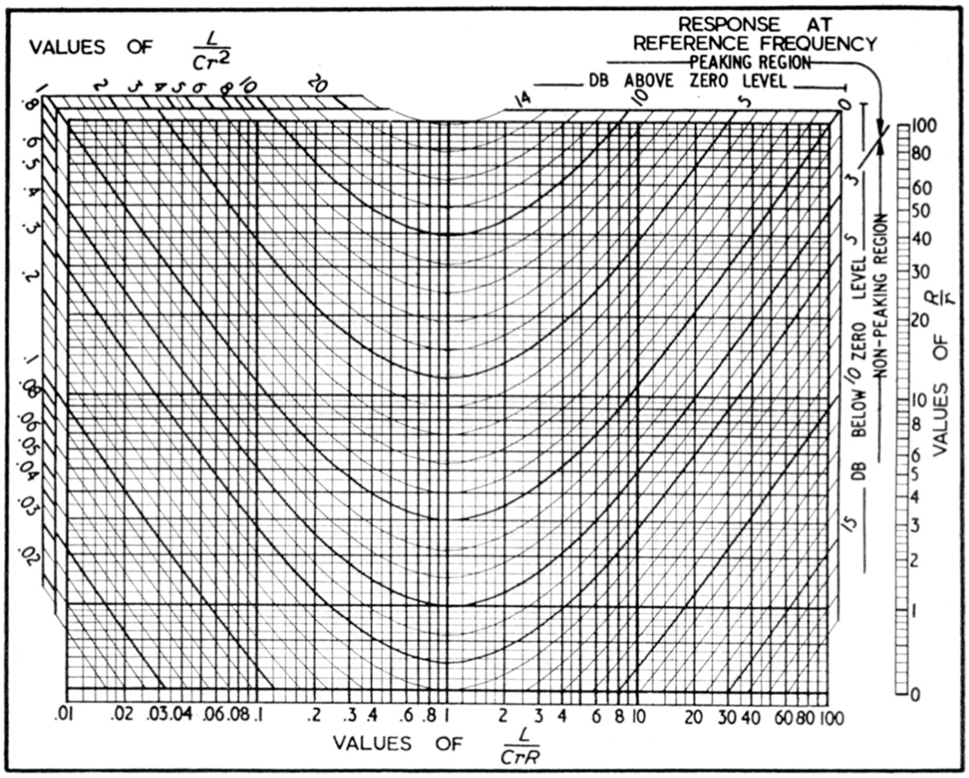

Fig. 11. Chart for determining the response shaping produced by various circuit element combinations. Values of L/CrR are calculated from the equivalent circuit of Fig. 13. The response shaping identified is given, normalized to the reference frequency obtained from Fig. 12, in Fig. 14.

The easiest way to consider how leakage inductance gets reduced by different sectionalizing arrangements is to draw a pattern for the leakage flux potential distribution through the winding. For a simple double winding arrangement this is shown at (A) in *Fig.* 6. Dividing one of these windings into two and disposing the two halves on either side of the other winding rearranges the pattern to (B).

Here it is clear that the portion of potential area contained in each triangular section, representing distribution of flux through the winding, is reduced to a quarter its previous value. The leakage inductance due to each of these sections is divided by eight. This is due to the fact that the leakage poten-

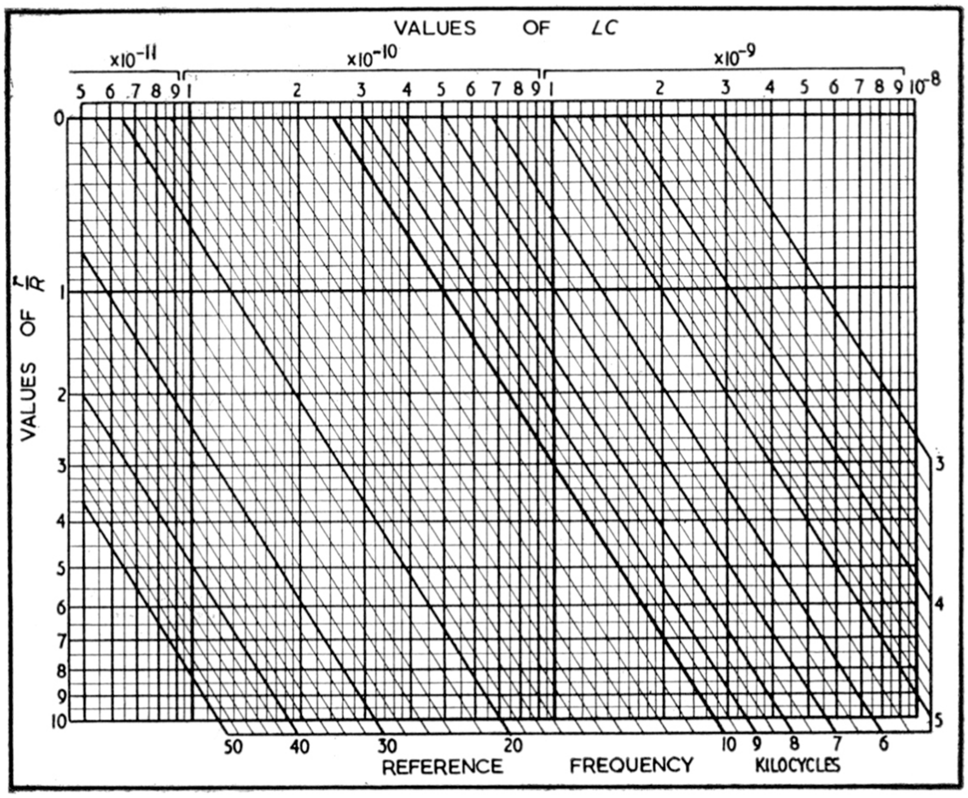

Fig. 12. Chart for determining the reference frequency for the response shaping identified by Fig. 11 and shown in Fig. 14.

tial produced is the product of the leakage flux at that point into the number of turns of the winding which that flux intersects. As each leakage flux potential area only acts on half the total number of turns in that winding, the integrated leakage potential due to leakage inductance in each section of the winding is 1/8 of that due to the whole winding in the arrangement of (A) in *Fig.* 6. So the leakage inductance due to the whole winding of (B) in *Fig.* 6 is one quarter of that at (A).

This is ignoring the leakage flux in the space between the windings which acts at a uniform leakage flux potential. Using a section factor of two, which is the comparison between (A) and (B) of *Fig.* 6, the leakage-flux potential at each of these spaces is divided by two. But the number of turns in which this induces a leakage potential is also halved. This means that the components of leakage inductance due to each space are divided by four, but because that there are now two spaces instead of one, the total contributed element of leakage inductance due to space between windings is one half of that in the single arrangement, assuming that each space in the second method of sectionalizing is of the same thickness as the original.

The leakage flux areas for two windings divided into three and two equal sections respectively are shown at (C) in *Fig.* 6. Here the succession of areas is not uniform and the leakage flux potential at different spaces between windings also differs, so a different series of factors will have to be used.

Comparison of this arrangement with that at (D) in *Fig.* 6 which still uses three sections of one winding and two of the other, shows that the latter arrangement results in much better reduction in overall leakage inductance. The relative dimensions and the factor they play on the over-all leakage inductance are shown in this figure for each of the cases.

On this basis *Fig.* 7 shows the factors for the number of sections used for the sectionalizing arrangements producing a maximum reduction of leakage inductance. In this schematic, the windings are in each case shown connnected in series. This is unimportant—the referred leakage inductance will be of the same magnitude to the impedance to which it is referred, regardless of whether windings are connected in series or in par-

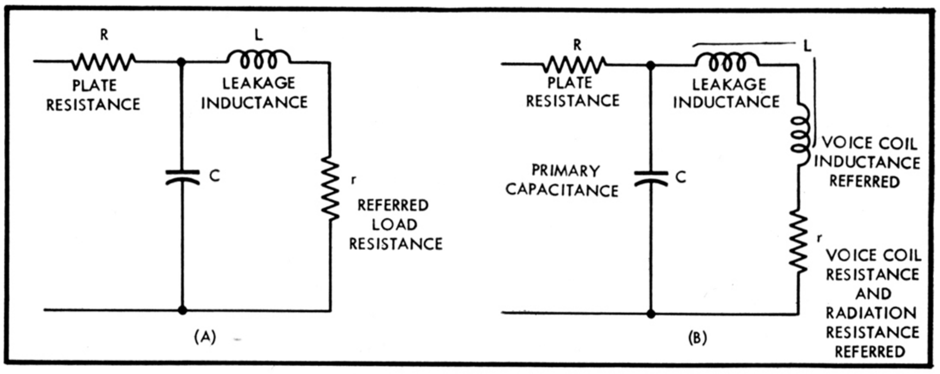

Fig. 13. Equivalent circuits for output transformer high-frequency response computation. (A) is the equivalent using a resistance load, and (B) is the equivalent using a loudspeaker load. The primary capacitance value used must include all effective capacitance across the primary, due to winding capacitance, distributed and lumped, tube plate-to-ground capacitance, wiring capacitance, and an additional capacitor, if used. Leakage inductance and load resistance must both be referred to the primary winding. The response predicted for (B) will be the current delivered to the loudspeaker at high frequencies. To obtain the voltage response, this can be combined with the impedance characteristic of **r** and the voice-coil inductance.

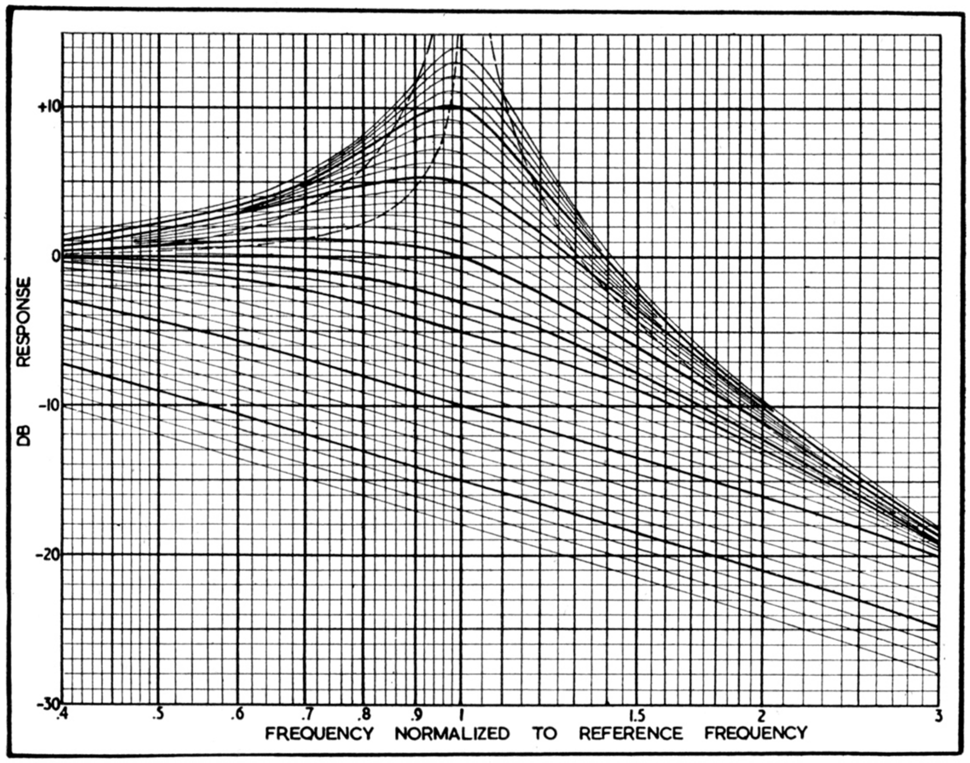

Fig. 14. Response shapings selected by the chart of Fig. 11. Actual frequencies can be calculated from the reference frequency given by Fig. 12. The dotted lines indicate the points of maximum slope on the curves (the outside ones) while the middle one indicates the point of the peak, which is useful in over-all response computation, particularly when the peak is not very high.

allel. In each case both the leakage inductance and the working impedance will be multiplied by the square of the number of sections used in transferring from parallel to series connections.

The best construction for producing a minimum leakage inductance uses windings with relatively long layer length and a few layers. To produce a low winding capacitance the layer length should be short and a large number of layers employed. In this way the inter-layer capacitance consists of a larger number of smaller capacitances in series. But this arrangement is much less advantageous for reducing leakage inductance. So the best method, where both quantities have to be reduced, is to modify the method of winding, using a vertical sectioning in addition to the horizontal sectioning. A section of a complete winding suitable for this purpose is shown at *Fig.* 8. Here only the high-impedance winding employs vertical sectioning to reduce the capacitance.

In designing a transformer where both factors are important, it is best to keep the number of horizontal sections down, because each intermixing, although it reduces leakage inductance, also makes it more difficult to reduce winding capacitance. The charts of *Figs.* 9 and 10 will prove useful in calculating the over-all leakage inductance of different winding arrangements and also in computing capacitance effects.

Over-all Performance

The data so far given can be utilized to calculate the electrical quantities of a transformer. But its performance is usually specified in terms of power handling, efficiency, frequency response, distortion, and so on, which does not specifically state the electrical quantities we have so far discussed. *These details can only be successfully evaluated on the basis of a complete amplifier design.*

Power-transfer efficiency is the only feature of a transformer which is inherent to the transformer at certain operating impedances, regardless of the circuit in which it is used. The frequency response and distortion characteristics are almost entirely dependent upon the tube circuits, and upon the feedback arrangements, where feedback is used.

Frequency Response

To facilitate calculation of frequency-response characteristics under these conditions, *Figs.* 11 and 12 help evaluate the high-frequency response in terms of the known circuit values: the source resistance due to tube a.c. resistance, the winding capacitance plus any primary capacitance due to wiring and tubes, and the leakage inductance, together with the load resistance; (A) in *Fig.* 13 shows the fundamental high frequency response circuit on which these calculations are based.

In practice the circuit with which the transformer is used is more likely to be that of (B) in *Fig.* 13 where the load also includes an inductance. If feedback is employed from the secondary of the transformer this will be taken from the junction between the inductance in the transformer due to its leakage and the inductance which forms part of the load.

Distortion

The distortion in output stages is due to (a) the transformer saturation at low frequencies, and (b) the effect of reactances in the transformer at other frequencies—sometimes also at low frequencies. These may cause the tube load line to open out into an ellipse, which produces an unfavorable loading condition for the tubes, causing an appreciable degree of distortion.

Stability

The transformer elements, leakage inductance, primary capacitance, and so on, also enter into the stability criterion for an over-all feedback amplifier. Also of course, any reactances in the load such as that due to voice-coil inductance, will also contribute to the stability criterion.

In designing an over-all amplifier all these factors should be taken into account and the writer suggests that the design department of a progressive transformer manufacturer should include facilities for advising amplifier manufacturers concerning the over-all design of equipment incorporating specific transformers; or, in reverse order, they should be capable of producing a transformer to suit a specified design and at the same time be prepared to give advice on the limitations of the design, with regard to loading conditions, etc.

This form of liaison, which for some reason seems to be unheard of, would result in considerable improvement in competitive amplifier design, in fact it would seem to be vital to further progress in this field.