Audio Transformer Design

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Continuing his discussion of transformers, the author covers several less known considerations in the arrangement of windings to obtain good performance over the entire audio-frequency spectrum.

POWER TRANSFORMER design has long since been reduced to a scientific process based on well established principles of economics. Only comparatively recently, however, has the appreciation begun to dawn on many transformer manufacturers that audio transformer design can be reduced to a similarly exact art.

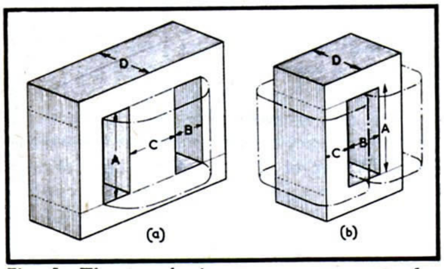

Fig. 1. The two basic core arrangements for audio transformers, with dimensions used for economic comparison indicated. (These shapes can also apply to C-core construction.)

The earlier method and one still used by quite a number of manufacturers was to work on a convenient rule of thumb. Any new design required was worked out as a kind of logical compromise based upon previous designs—"we used 10,000 turns on transformer A which was such and such a size and 6,000 turns on transformer B which was so much smaller, so 8,000 turns should be about right for this job," was typical of the kind of reasoning used. The important aspect of economics—comparison on a cost basis—has always been in the background with successful enterprises, but there are other aspects which need consideration to produce the best products of any particular type.

Choice of Core Shape and Material

The first step in the design of a transformer is the choice of a suitable core shape and material. The best shape to use will depend upon: the type of transformer; whether frequency response, efficiency, or working signal level are the predominant factors in the design; whether or not the core will be polarized by unbalanced d.c.

The two basic forms of core construction are shown at *Fig.* 1, the position occupied by the winding being indicated by chain dotted lines. Although both arrangements are pictured as built up of stampings, either of them can also be applied to C-core construction. The essential dimensions as referred to in the graphs given in this article are clearly marked.

If the transformer is to provide the maximum energy transfer in the available space, *Fig.* 2 shows suitable relative dimensions plotted against the relative cross section of winding and core, B/C. It will be noticed that the combination of values given represent elongated window shapes and large stacks of laminations. These proportions are based upon perfect winding facilities and the assumption that no space is lost due to the tendency of the wire to remain curved on inside corners. In practice this tendency will slightly modify the ideal dimensions.

Figure 3 shows the economic proportions for achieving maximum frequency band when d.c. components are balanced so the core is not polarized, based on the ratio of primary inductance to leakage inductance of a simple layer-wound transformer. This does not take into consideration the effect of winding capacitance—no general presentation could be derived to include this because of the variety of winding forms that can be adopted for reducing both leakage inductance and winding capacitance, and the variation in relative importance of these quantities with individual applications. As a general principle, a smaller component gives the best chance of reducing over-all winding capacitances.

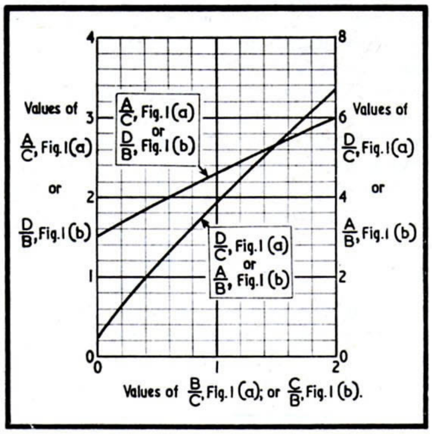

Fig. 2. Theoretical economic proportions of cores for maximum energy-transfer efficiency.

Figure 4 shows the economic proportions for components where d.c. polarizing is present. These proportions are based upon the attainment of specified inductance in a given physical bulk with maximum efficiency.

Another factor that may influence choice of core shape and material is the maximum signal level. The core must be able to handle this at the lowest frequency required without producing distortion due to saturation of the core. Where a large component is no disadvantage for other purposes, a large cross section of ordinary-grade transformer iron provides the simplest and cheapest solution. For some applications, size and/or weight may be of importance in the over-all design of the equipment, while size can also adversely affect available frequency response at the high-frequency end particularly where step-up to a high impedance is required. In such cases, it is advisable to use one of the special alloys developed for high maximum flux density.

At the opposite extreme, transformers required for low-level input circuits

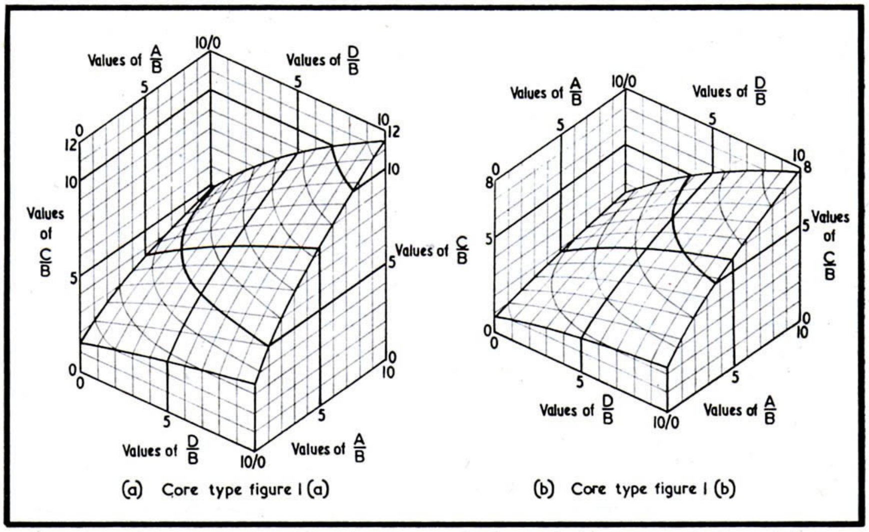

Fig. 3. Economic proportions for maximum ratio of primary inductance to leakage inductance.

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should use a core material providing maximum initial permeability. Special alloys are available for this purpose.

Components required to carry appreciable polarizing d.c. will usually gain little by using an expensive core material. Ordinary transformer iron is usually the economic choice for these.

Another feature influencing choice of core may be the necessity for providing maximum discrimination against stray field pick-up. Astatic construction, using the arrangement of (b) in *Fig.* 1, with both windings of the transformer equally divided on both limbs, gives best possibilities in this direction. Where this requirement is not present, the construction of (a) will usually provide maximum efficiency and the best possibility of wide frequency range, whether laminations or C cores are used.

Toroidal construction is technically better than either of the constructions shown at *Fig.* 1 but has the disadvantages for the majority of applications of greater cost and bulk. The more conventional designs lend themselves to more compact construction.

Winding Arrangement

Having chosen a suitable core, the next question is how to arrange the winding. *Figure* 5 shows the two basic arrangements of winding disposition applied to the core of (a) in *Fig.* 1. For audio transformers a low value of leakage inductance combined with high primary inductance is always a necessity, for which purpose the layer arrangement of (a) in *Fig.* 5 is invariably many times better than the slab arrangement of (b). Each winding may be further sectionalized in order to provide improved coupling, particularly at the high frequencies.

Sectionalizing can influence two of the electrical properties of the transformer which exert a control on high-frequency response in varying proportions with different applications: leakage inductance and winding capacitance.

WINDING ARRANGEMENT	N	N^2
Primary / Secondary: PRIMARY, SECONDARY	1	1
Primary / Secondary: SECY. PRIMARY SECY.	2	4
Primary / Secondary: PRY. SECONDARY PRIMARY SECY.	3	9
Primary / Secondary: SECY. PRIMARY SECONDARY PRIMARY SECY.	4	16
Primary / Secondary: PRY. SECY. PRIMARY SECY. PRIMARY SEC.	5	25
Primary / Secondary: S. PRY. SECY. PRY. SECY. PRY. S.	6	36
Primary / Secondary: P. SECY. PRY. SECY. PRY. SECY. PRY. S.	7	49
Primary / Secondary: S. PRY. SECY. PRY. SECY. PRY. SECY. PRY. S.	8	64

Fig. 6. Economic sectionalizing arrangements for producing a maximum reduction of leakage inductance. N signifies the effective reduction of spacing thickness between sections, and N^2 the effective reduction in total winding depth.

Reducing Leakage Inductance

To reduce leakage inductance only one method of sectionalizing has any effect—sandwiching the windings. The first step is to divide one of the windings into two equal parts and place one half below and the other above the other winding. The next step is to divide one winding into two parts and the other into three. Sometimes the winding divided into three parts uses equal parts, but this is not the best arrangement for leakage inductance reduction; the part sandwiched between the other winding should be half of the total turns in the winding, the other two parts each being quarters.

Figure 6 shows a succession of economic arrangements from the viewpoint of leakage inductance reduction. Series connection is shown for simplicity. Parallel or series/parallel connection will not alter the over-all leakage inductance referred to a specific number of turns.

In the simple arrangement where each winding is in one section, the effective leakage flux path cross section is one-third of the total winding depth, plus the thickness of insulation between the windings. Usually the thickness of insulation between the windings is negligible compared to one-third of the total winding thickness, so its relative effect on leakage inductance can be ignored. As the windings are split successively into more sections, the effective winding thickness is divided by the factor N^2. The thickness of the effective space between windings is equal to the thickness of each layer of insulation between sections divided by N. Values of N and N^2 are shown in Table I. These figures mean that if the winding occupies the same total space and the same insulation thickness is always used between winding sections, the original total winding thickness and insulation thickness can be divided by the factors shown and the results added to give the effect of the arrangement on leakage inductance.

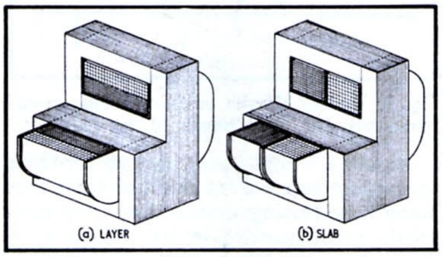

Fig. 5. The two basic dispositions of windings. The layer arrangement at (a) results in very much lower leakage inductance than the slab arrangement of (b).

Example: Total winding thickness 0.75 in., and insulation thickness .02 in., then the leakage flux cross-section for the simple winding is 0.25 in. plus .02 in., a total of 0.27 in. An arrangement giving $N^2 = 25$, and $N = 5$, will reduce the leakage flux cross-section to .01 in. plus .004 in., a total of .014 in. Leakage inductance will be reduced in the proportion 0.270: .014. Notice that the proportion of leakage inductance due to spacing between sections rises as a greater number of sections is used; this fact limits the useful reduction in leakage inductance that increased sectionalizing can achieve.

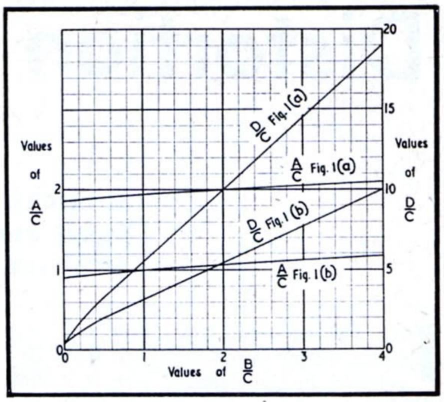

Fig. 4. Economic proportions for components carrying polarizing d.c.

Reducing Winding Capacitance

The second purpose of sectionalizing windings is to reduce winding capacitance. A different form of sectionalizing is effective for this reduction. To estimate the effect of sectionalizing on winding capacitance, its consideration must be divided into two sections: capacitance due to the internal structure of the winding; and capacitance to adjacent sections of the other winding or to interwinding screens.

In transformers with high ratios, the low-impedance winding is usually so near to ground potential throughout, from the viewpoint of the high-impedance winding, that screening would be an unnecessary refinement except perhaps for the purpose of avoiding capacitance transfer, which can occur if the low-impedance winding is not grounded at all. Where the impedance of both windings is more nearly equal, interwinding screens can be very useful in avoiding undesirable capacitance between high-signal-potential parts of both windings. However, with the simpler arrangements it is still possible to avoid the necessity of screens by ensuring that the high-signal-potential turns of one of the adjacent windings are near to a grounded, or zero-signal, point in the other winding.

Figure 7 shows the method of sectionalizing one of the windings to reduce its capacitance to others, and Table I shows the effect of different numbers of vertical sections on capacitance to the adjacent winding and on the internal capacitance of the winding itself for both constructions shown. The arrangement at (a) represents the simple arrangement where only one side of the winding is sufficiently close to the screen or other winding to contribute appreciably to resultant capacitance. That at (b) shows a winding sandwiched between two effectively grounded layers, equally spaced from it.

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The effective capacitance of the adjacent winding will depend upon what point in the high-impedance winding is grounded, or at zero signal potential. Only two positions for the zero signal point are commonly found: at one end, or at the center point of the winding. The tabulation of *Fig. 7* shows the effect of sectionalizing for both conditions.

From the foregoing it appears that the exact arrangement as regards sectionalizing of windings depends upon its effect upon leakage inductance and winding capacitance. The final choice of arrangement now depends upon three main factors: the distribution of circuit components, the position of zero-signal points, and the mode of operation.

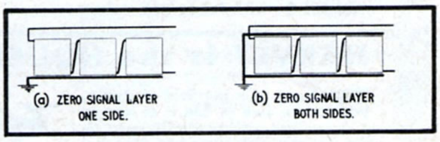

Fig. 7. Vertical sectioning employed to reduce winding capacitance. Its effect, as shown in Table 1, depends on the disposition of screens or adjacent windings at sensibly zero signal potential.

Distribution of Circuit Components

The external circuit values with which the transformer operates determine the relative importance of leakage inductance and winding capacitance.

An output transformer designed to feed conventional loudspeaker loads will be feeding an inductive load, so leakage inductance in the transformer will be relatively unimportant as regards frequency response. Even the simplest winding arrangements will result in a leakage inductance that is quite small compared to the voice-coil inductance of the loudspeaker(s) used as load. Attention to reducing the capacitance of the primary winding is likely to be more important, although for many applications, using tetrode or pentode output stages, a fair degree of capacitance is required, so the simple winding arrangement is no disadvantage.

For input, interstage, or line transformers, leakage inductance and winding capacitance assume varying degrees of importance according to the operating impedance used. In some instances the upper end of the frequency band will be controlled by the LC product of leakage inductance and winding capacitance, in which case both qualities require to be reduced so as to produce a minimum product value. In applications where all circuit impedances are lower, leakage inductance may be the most important factor. in which case perhaps winding capacitance can be ignored. In other cases, such as input transformers design for operation from dynamic transducers, the leakage inductance will be swamped by the inductance of the transducer, so winding capacitance is the limiting factor which must be reduced to a minimum.

Where capacitance assumes important relations, the position of the zero signal point in the high-impedance winding will be an important factor in deciding what winding arrangement to use.

Figure 8 shows a number of winding arrangements of the type employed to reduce leakage inductance, together with their effective capacitance, expressed in terms of the capacitance between the high-potential side of the high winding and an adjacent winding or screen connected to ground. These values are listed for both center-point and one-side zero-signal arrangements.

As shown in the Table I, choice of vertical sectioning for reducing capacitance will also depend upon the position of zero-signal point in the high-impedance winding.

Mode of Operation

Output transformers may be for application in circuits employing either Class A or Class B operation of the output tubes. For Class A applications, it

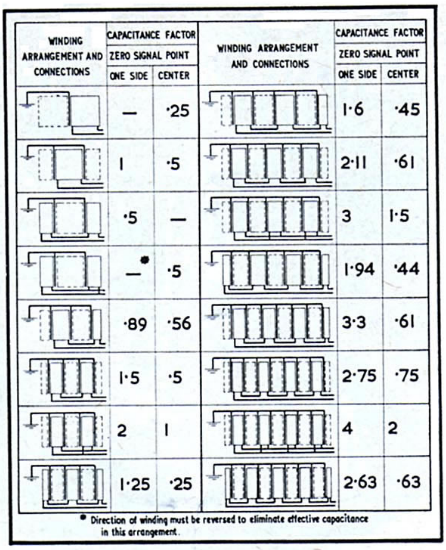

Fig. 8. The effect of different winding arrangements and connections, used for leakage-inductance reduction, on winding-to-winding or winding-to-screen capacitance. The capacitance factor shown gives the effective over-all capacitance in terms of that between average adjacent windings, or winding and screen.

is important only that the whole of the primary should be uniformly well coupled to the secondary. For Class B applications, one half of the the winding is out of action during each half cycle, so the coupling must be a maximum for each half winding to the whole of the secondary. This means that the method of connecting up the sections, combined with the sectionalizing arrangement used, should be such that no part of the secondary winding is spaced away from either of the halves of the primary winding.

Figure 9 illustrates this with a simple example. The arrangement at (a) provides uniform coupling between the whole primary and the whole secondary and would, from this viewpoint, be satisfactory for class A operation; but for Class B operation, one half of the secondary winding is always sandwiched in the middle of an inactive half of the primary winding; so the space occupied by the intervening portion of inactive winding will add an unnecessarily large proportion of leakage inductance between whole secondary winding and the active half of the primary winding.

The arrangement of (b) maintains uniform coupling between the whole primary and the whole secondary, but in this case the coupling between the whole secondary and each half primary is reduced to a minimum. It may not at once be obvious that the coupling between both half primaries and the whole secondary is identical in this arrangement. The half primary sandwiched between the secondary sections forms a coupling similar to the second arrangement shown in *Fig.* 6. The arrangement for the half of the primary made up of the two outside quarters with respect to the whole secondary is also equivalent to the same basic arrangement, but it would appear at first sight that the total winding thickness is greater in this case. However, the inactive half primary now occupies a place in the secondary winding which is at zero-leakage-flux potential from the viewpoint of coupling with the active half primary, so the space occupied by the inactive half primary, can be ignored in computing the leakage inductance for the active half.

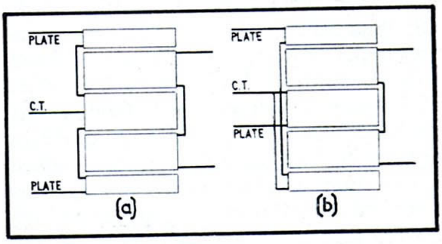

Fig. 9. An example of coupling arrangement suitable for Class B or alternative winding operation. (For explanation see text)

For other types of transformer, alternative windings may be required for different purposes. In such designs the arrangement should be devised so that maximum coupling is achieved between each of the alternative windings and the common winding. The same principle as that just outlined for the design of Class B transformers can also be applied here by placing each of the alternative windings in such a position that it occupies a region of zero-leakage-flux potential in relation to coupling with the other alternative winding.

TABLE I

Capacitance Factors for Vertical Sectionalizing

Number of Vertical Sections	Capacitance Factors				
	Distributed Capacitance Component	Inter-winding, or winding-to-screen			
		Figure 7 (a)		Figure 7 (b)	
		Zero signal point		Zero signal point	
		One side	Center	One side	Center
1	1	—	.25	1	.5
2	.25	.125	.125	.75	.25
3	.11	.185	.102	.703	.204
4	.063	.219	.094	.688	.188
5	.04	.24	.09	.68	.18
6	.028	.255	.088	.676	.176