How Good is an Audio Transformer?

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A thorough understanding of transformers is essential to the selection of the proper type for any particular application. The fundamentals are here presented by the author to introduce the series on one of the most important components in high-quality audio equipment.

THERE WAS A TIME when audio transformers were specified simply by turns ratio. An interstage transformer would be designated, according to ratio, e.g., 3: 1 or 5: 1. But one component would give much better performance, although having the same turns ratio as another. The modern transformer manufacturer knows that there is far more to designing a good transformer than just putting windings on a core so as to have the correct turns ratio. Each design must in fact be suited for the particular job in hand. To help the prospective user, the component is generally specified by the circuit for which it is intended, e.g. "10,000-ohm plate to single grid," together with some statement of frequency range. This is much more informative, but a still further and more detailed understanding of audio transformers will enable them to be used to best advantage in every application.

Any audio transformer is essentially a matching device, but no transformer is a perfect matching device because it introduces its own losses and defects. It is the designer's job to see that these losses and defects are kept to suitable proportions. If he has done a good job, then the user can get the best performance from the component by following the manufacturer's recommendations as to circuit values. But it would not be economic to design a different transformer to suit every possible application or circuit, so a standardized design often has to cover a range of uses. A perfectly good transformer, connected into a circuit unsuited for it, will give poor results, but correct understanding of the problem can help rectify these deficiencies.

How Big Must it Be?

A popular fallacy has been that audio transformers always follow the principle "the bigger the better." Sometimes size is essential to quality, but for other applications the smaller component is the better one.

All modern transformer core materials have a well defined saturation density. Magnetization above it will considerably distort the current waveform, and the distortion will reflect into the circuit. The saturation density will correspond to different voltage levels at different frequencies, so the handling capacity of a transformer depends on the frequency considered. A winding that will accept 5 volts at 60 cps before distorting will accept 10 volts at 120 cps.

Applying this fact to audio power transformers, a component rated to deliver 10 watts over a frequency range down to 60 cps will deliver considerably more power if the low-frequency cut-off is raised to, say, 240 cps. Conversely, a smaller transformer may be used for the same power rating if a higher cut-off is employed. In practice, the fact that only signals of low level are needed at the low-frequency end of the audio spectrum enables smaller transformers to be employed than would be possible if full output were required down to, say, 60 cps.

Another factor that affects size is the presence or otherwise of d.c. polarizing. Where plate current passes through one winding (not in push-pull), the core becomes polarized. To minimize this polarization, a gap is left in the core by the manufacturer, according to the intended current. Polarization reduces the allowable a.c. magnetization, but the gap in the core reduces the primary inductance unless the turns are increased. So to achieve suitable primary inductance and satisfactory a.c. magnetization limits, without excessive insertion loss, the presence of polarizing current requires more turns on a larger core size.

For input transformers—line to grid, or microphone to grid—size is seldom an advantage, the best transformers designed being of small size. For interstage transformers, where appreciable voltage swing is required, a slightly larger transformer may be necessary.

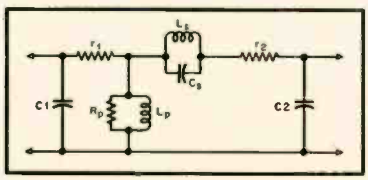

Fig. 1. Equivalent circuit of audio transformer.
C_1 = primary capacitance
C_2 = secondary capacitance
C_3 = interwinding capacitance
L_p = primary inductance
L_s = leakage inductance
r_1 = primary resistance
r_2 = secondary resistance
R_p = core loss referred to primary

For driver transformers, where power must be delivered to the grid circuit, considerably larger sizes are required.

Its Electrical Specification

The transformer's electrical properties have a direct bearing on its performance, but the user will not necessarily be bothered with them directly. His concern is with the performance of the finished article. The principal properties are shown for reference at *Fig.* 1, which will assist in understanding the behavior of the transformer under different conditions, and what part each contributes. This is one way of representing the equivalent circuit of any audio transformer. For convenience, the fact that the transformer provides a step-up or step-down is not shown in the diagram. This action of the transformer may be regarded as perfect, its imperfections being presented in the circuit values of *Fig.* 1. The legend under the diagram explains what each symbol represents.

There are four elements shown as shunting the transmitted signal—primary and secondary winding capacitance, primary inductance, and core loss referred to the primary.

There are four elements shown as in series with signal transmission—primary and secondary winding resistance,

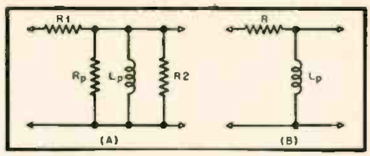

Fig. 2. Equivalent circuit for low-frequency cut-off, in a direct-coupled a.f. transformer. (A) Complete arrangement: R_1 = primary source impedance; R_2 = secondary load impedance. (B) Simplified equivalent of (A): R = parallel combination of R_1, R_p, and R_2.

leakage inductance, and interwinding capacitance.

All these circuit elements must be referred to one winding when considering their effect. If the primary is the chosen reference winding, then elements actually due to the secondary winding or its associated circuit must be "referred" in value by a factor of the turns ratio squared. Suppose the ratio is 3: 1 step-up, then secondary winding resistance is divided by 9 and its capacitance

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multiplied by 9 in referring to the primary. Usually the "referred" winding resistances of both windings are of the same order, but the referred winding capacitance of the high winding is much larger than that of the low one (about 9 times for 3:1 ratio). Hence the effect of the low-winding capacitance can often be ignored, only that of the high one being taken into account.

Insertion Loss

At a middle frequency, the shunt reactances will be high enough to exercise negligible effect, while the series reactance of L_s will be low enough to ignore, so the transformer is virtually a "T" resistor network, the attenuation of which can be calculated with reference to external circuit values—also usually resistances only—at mid-frequency. This attenuation, essentially a measure of power loss, is known as the insertion loss of the transformer.

For input and interstage transformers, where voltage transfer is the important feature, insertion loss is not generally given serious consideration. But for driver and output transformers, where insertion loss means valuable watts are lost, it must be considered. Insertion loss may be expressed in db, when the fractional power ratio corresponding to the db figure gives the proportion of input power reaching the output, or it may be expressed directly as a percentage. For example an insertion loss of 1 db represents an efficiency of approximately 80 per cent.

For a given transformer size, correctly designed, the ratio of r_1 and r_2 to R_p is fixed by the geometry of the component. Variation of turns and wire gauge to suit, varies winding resistance and referred core-loss shunt in the same proportion. Thus a winding with too few turns results in low core-loss shunt, while too many turns produces excessive winding resistance. Conversely, from the user's viewpoint, connecting a transformer to circuits of lower impedance than design values introduces high series loss due to winding resistance, while connection to higher impedances results in serious shunt losses due to core magnetization.

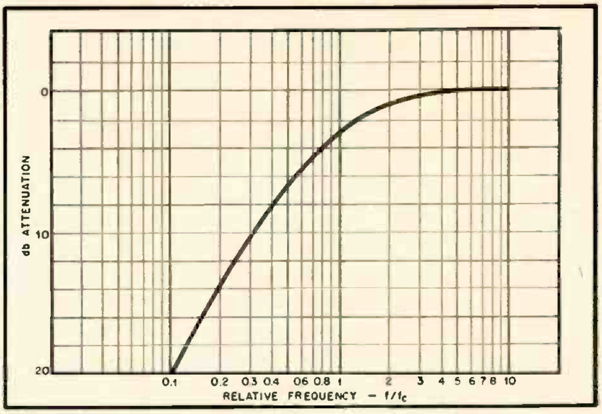

Fig. 3. Low-frequency cut-off attenuation characteristic, 6 db per octave.

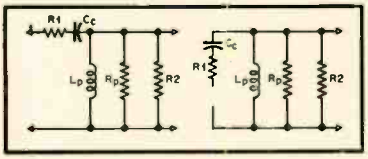

Fig. 4 (left). Equivalent circuit for low-frequency cut-off in a parallel-fed a.f. transformer: C_c = coupling capacitor. Fig. 5 (right). Rearrangement of Fig. 4 to show it as a resonant circuit.

In generally, a variation of impedance results in a deficiency in frequency response as well, and the choice of the number of turns in design must be a compromise to achieve good response to both low and high ends of the spectrum.

At low frequencies, the effect of L_s, C_s, C_1, and C_2 is negligible, but that of inductance L_p will become appreciable. For the purpose of comparative response, the values of winding resistances r_1 and r_2 can generally be ignored as small compared to the circuit resistances R_1 and R_2 to which the transformer is connected. Thus the circuit can be redrawn as at *Fig.* 2 from the viewpoint of relative l.f. response. At (A) the relevant values are shown, R_1 being the source impedance—i.e., the plate resistance of the tube if the transformer is connected in a plate circuit; R_2 is the secondary load resistance, if any, referred by turns ratio squared to the primary side. For example, a shunt resistor of 1 megohm on the secondary of a 5:1 step-up will give a referred R_2 of 1 megohm divided by 5^2 or 25, which is 40,000 ohms.

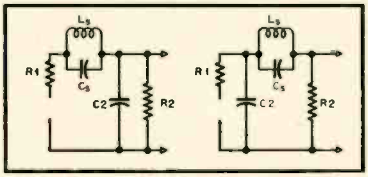

Fig. 6 (left). Equivalent circuit for high-frequency cut-off in a step-up transformer, and Fig. 7 (right), in a step-down transformer.

The shunting effect of L_p must be considered relative to the parallel resultant of R_1, R_2 and R_p. Thus (B) in *Fig.* 2 shows a simplified theoretical form of the circuit, where R is the resistance of R_1, R_2 and R_p in parallel. This circuit produces a simple 6 db/octave l.f. cut-off, of the type shown at *Fig.* 3, in which the 3-db point is the frequency where the reactance of L_p is equal to R. Thus the cut-off frequency can be modified by changing either L_p or R. As L_p and R_p are fixed by the transformer, the remaining possibilities for adjusting l.f. cut-off are R_1 and R_2. Reduction of the effective parallel resistance of these two will lower the l.f. cut-off, extending the frequency range.

With a direct-coupled transformer, where the core is polarized, the core is gapped so that the highest possible inductance is achieved when the current for which it is designed passes through the winding. It is wasteful to work the transformer at a current differing appreciably from this value.

A direct-coupled transformer operating in a push-pull plate circuit does not have its core polarized, so a smaller component can be used, and the circuit of *Fig.* 2 can be applied, taking care that all impedances are referred to either the whole, or half, of the primary winding, correctly. However, the inductance varies widely with both frequency and level, so the response shown at *Fig.* 3 will not be applicable, but the same principle for adjusting l.f. cut-off applies.

Distortion is closely associated with l.f. response because it appears most strongly at this end. Steps that improve l.f. response also reduce distortion due to harmonics in the magnetizing current.

Sometimes transformers are parallel fed, to avoid passing the plate current through the primary winding. Since a coupling capacitor is then necessary, its reactance also becomes effective at low frequencies, so the circuit for l.f. response takes the form shown at *Fig.* 4. Here R_1 is the effective resistance given by the plate resistance of the tube and its coupling resistor in parallel; R_2, as before, is the secondary load resistance, if any, referred to the primary. This circuit is in the form of a resonant circuit, seen more clearly as redrawn at *Fig.* 5, where R_1 is in series with the resonant components C_c and L_p, and the resistances R_p and R_2 are in shunt. For this reason, larger values of R_1 or smaller values of R_2 increase the damping (or reduce the Q) of the resonant circuit.

Less-than-critical damping results in a l.f. peak in the vicinity of cut-off. Critical, or more-than-critical, damping, eliminates any tendency to peak. Choice of suitable values for R_1, R_2, and C_c can result in best possible operation of the transformer in a circuit, as will be shown in detail in following articles.

Response at High Frequencies

At high frequencies the effect of L_p, and C_c if used, will be negligible, and where any appreciable transformation ratio is employed, one of the winding capacitances may usually be neglected. Thus *Fig.* 6 shows the h.f. circuit equivalent for a step-up transformer, while

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TABLE II

	Preferred change in level db
From speech to speech	0
From music to speech	−4 to −5
From speech to loud-starting music	+2
From speech to quiet-starting music	+2 to +3
From speech to interval signal (Bow Bells)	−19

Voltage Regulator Tubes

An article on the use of neon voltage regulator tubes by C. Tuppin appears in the September 1950 *Toute la Radio*. Techniques for the stabilization of both d.c. and a.c. voltages are discussed, and trigger tubes are mentioned briefly. Of importance is the table of regulator tubes available in France. Some of these tubes are capable of stabilizing voltages as high as 340 volts while others have current ranges up to 200 ma. Most of these tubes are not marketed in this country, although they would appear to be quite useful in many applications where designers are now forced to use series or parallel connection of available tubes.

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Fig. 7 shows that for a step-down type. As in the previous section, it is assumed that winding resistances are negligible in comparison with the circuit impedances.

A complicating factor is the interwinding capacitance C_s, so it is usual to take steps to eliminate its effect. Some transformers incorporate shields between windings, connected to ground, so that interwinding capacitance is replaced by winding-to-shield, i.e. to ground, capacitance, effectively increasing existing winding capacitance slightly.

Where shields are not employed, it is

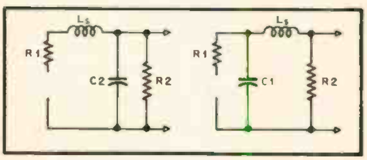

Fig. 8 (left). Elimination of C_s from Fig. 6, and Fig. 9 (right) from Fig. 7.

generally possible to connect the transformer so as to practically eliminate the effect of interwinding capacitance. Interwinding capacitance is the capacitance between the layers of turns that are nearest together in the two windings. These layers will be turns electrically close to one end of their respective windings. By connecting the windings into the external circuit so that the signal potential to ground from one of these ends is zero, the interwinding capacitance will become virtually the capacitance from the other winding to ground. If the ends nearest together in both windings have zero signal potential to ground, the effect of interwinding capacitance is completely eliminated, not even adding to effective winding capacitance, because there is no signal potential across it. (Any d.c. potential between windings will not produce capacitance currents.)

When the effect of interwinding capacitance has been eliminated, the circuits of *Figs.* 6 and 7 become those shown at *Figs.* 8 and 9 respectively. Now, as in the l.f. case, each circuit becomes a simple resonant circuit, in which the impedance connected to the low side of the transformer is series damping, while that connected to the high side is shunt damping. *Figure* 10 shows the h.f. response due to (a) less-than-critical damping, (b) critical damping, (c) more-than-critical damping.

Common cases where inadequate damping gives rise to a h.f. peak are interstage transformers operated in the plate circuit of triodes, and output transformers for tetrode or pentode tubes. Careful attention to the circuit can eliminate an undesirable peak or loss and produce the best possible response.

The internal properties of an audio transformer that set a limit to its frequency range at the upper end are its leakage inductance and the winding capacitance of the high side (including additional capacitance connected across the winding externally, such as grid input and strays). The ultimate cut-off frequency is inversely proportional to the square root of the product of this inductance and capacitance. Both these quantities increase with the size of the transformer so it is clear that smaller transformers have an inherently higher frequency range.

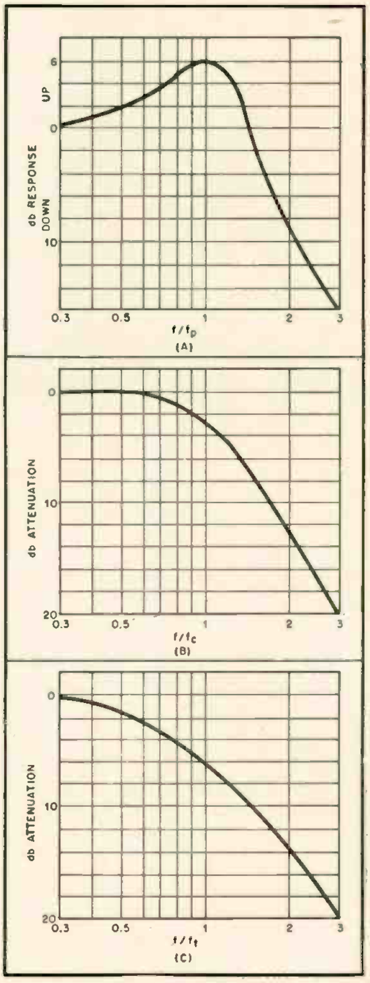

Fig. 10. Attenuation responses for high-frequency cut-off; (A) less-than-critical damping; (B) critical damping; and (C) more-than-critical damping.

Successful operation of any transformer depends appreciably upon the circuit in which it is worked, and the manufacturer's specification does not wholly determine how good any particular transformer is for the job in hand. Simple methods of measuring up the qualities of a transformer and of determining circuit modifications for optimum performance will be discussed in subsequent articles.