audiology

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Output Transformer Design Considerations

SUCCESSFUL DEVELOPMENT of an audio power amplifier depends greatly upon output transformer characteristics, whether the principal equipment objective be economy or quality. While some pertinent features may be specified readily in simple numerical form, other characteristics, important to high-fidelity equipment, are of such involved nature that simultaneous development of circuit and transformer is almost essential. However, experience and analysis demonstrate several principles upon which important choices are based, and form a basis for judgment applicable to either design or purchase.

Basic purposes of the output transformer are coupling tubes to the load with d.c. isolation, and transformation of the load impedance to a value suitable for efficient tube operation. To avoid adversely affecting amplifier performance, the transformer preferably would be highly efficient over the desired band, and would not cause objectionable distortion at low frequencies. Apparently then, refinements characterizing high-quality output transformers simply *permit* good circuit performance, rather than *cause* it to be good.

Response

The frequency range over which relatively uniform transformation may be had is controlled largely by the source and terminating impedances, the shunt winding inductance, and the leakage inductance. With fixed source and load impedances, the ratio of these inductances sets the ratio of limiting high and low frequencies; ratio values range from less than 200 for lowest cost equipment, to 10,000 or more in costly idealizations. Chief determining factors are the core material, prevailing d.c. magnetization, and the winding configuration. To the extent that capacitances and changes in core permeability may be neglected, coil turns do not influence the bandwidth in octaves, since both self inductance and leakage inductance vary as the square of the number of turns. While not affecting the response-curve shape, the number of turns sets the position of the curve in the frequency spectrum.

Assume a certain ratio of these inductances, and no other reactances of importance, and let g equal the ratio of source impedance to load impedance. The ratio of high and low frequencies at which the response is down 3 db is then proportional to the factor $(g+1)^2/g$, which has minimum value when $g=1$. Thus, equal source and load impedances is the least desirable combination if wide-range response is a principal object. Core distortion considerations indicate that g should be made low rather than high; that is, the source impedance would preferably be very low compared with the load impedance. Most significant reduction of g is accomplished with negative feedback in the amplifier, which in turn causes additional complication in the transformer design.

Distortion

Low-frequency waveform distortion in iron-core transformers occurs because the shunt winding inductance is not constant throughout the signal cycle. Relatively little quantitative material has been published, and there is considerable variation among core materials of otherwise similar character. General trends of the data have been analyzed, however, and are reviewed briefly here.

Let X/R equal the ratio of the open-circuit reactance of the transformer primary winding to the parallel combination of source and load resistances. X may vary widely with frequency, flux density, and changes in d.c. magnetization. With X/R

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This is the first of a series of short articles covering various aspects of audio engineering on a not-so-technical level, yet with information which can be relied upon. During the next few months, Mr. Ayres will discuss resistance-coupled amplifier charts, the effect of feedback upon tube characteristics, feedback from the output transformer primary, from the secondary, and from a tertiary winding. Æ would welcome readers' comments, as well as suggestions for further subjects to be covered in the future. Ed.

as the independent variable,

1. Distortion at a given flux density varies roughly inversely as X/R for values of this ratio above about unity.
2. Distortion variation with flux density for constant X/R is of the general form $y=a+bx^n$ (a straight line on log-log paper) in the flux density ranges of approximately 200 to 8000 gauss for silicon steel, and 300 to 3000 gauss for the more common nickel alloys.
3. Distortion falls only very slowly as the flux density is reduced below about 200 gauss.
4. Direct-current magnetization results in even as well as odd harmonics, and may increase the total distortion materially.

For minimum transformer distortion, the a.c. flux density and d.c. magnetization would be minimized, and the ratio X/R made as large as practicably possible. But there is no useful object in making distortion due to transformer nonlinearity much lower than that due to other causes at the low frequency in question.

Efficiency

Losses at mid-frequencies are usually considered to be due to winding resistances only. Aptly named "copper efficiency" is easily estimated in design, and may be tested by simple resistance measurements. Notion of the error at low frequencies may be gained from consideration of a transformer with a 2-lb. core of high-silicon steel, operating at 10 watts output with a flux density of 5000 gauss at 60 cps. Total core loss would be about 0.4 watt. Were the copper efficiency (say) 92 per cent, the true efficiency would be more like 88 per cent.

While heating is ordinarily not the problem in output transformers that it is in power transformers, the cost per watt-hour is much higher. But from the designer's standpoint, increased over-all value of an equipment development through improvement of output transformer efficiency is often small compared with the increased component cost. Almost any successful design, whether commercial or laboratory, is a wisely chosen set of compromises, and choice of operating efficiency is no exception.

When necessary reduction in physical size warrants added cost, significant miniaturization of low-level audio transformers is possible through the use of nickel-steel cores. But if transformer requirements dictate maximum operating flux densities as high as several thousand gauss or more at the lowest intended frequency of operation, nickel-steel core material is generally inferior to high-silicon steel. Of the latter, the grain oriented variety is a preferred type, and is available in woundloops and as punched laminations, with neither form always having advantage over the other. Additional output-transformer miniaturization is possible by improved utilization of the core window area, or by selection of a more favorable core shape.

Assuming such improvements have already been incorporated, further size reduction (for a given specification on response and distortion) can be had only with reduced efficiency. The extent to which one may exploit this possibility depends largely upon the associated circuit, and over-all equipment considerations of size, cost, and practicability of manufacture.

Particularly for wideband arrangements in which extensive negative feedback is employed, there are important transformer details "not shown in the circuit diagram." These are complex coupling and capacitance structures resulting from interleaving of the various windings, and are not readily subject to design calculation or adequate description in simple specification form.

Thus one frequently finds that superior power-amplifier designs have been based upon simultaneous development of circuit and output transformer, with each adapted to accommodate the other.

Manufacture may then consist of duplicating the model declared optimum for the particular circuit, with just enough tests along the way to assure the required closeness of duplication. To the manufacturer, this is an obviously workable plan. To the casual amplifier construction enthusiast who wants top quality at moderate power, the implication is that best results, for effort expended, may probably be had by purchase of an output transformer of published overall characteristics. There is often a strong element of buying on faith, and likelihood of satisfaction is improved through buying from one of the now numerous manufacturers who specify the circuits with or for which their transformers were developed.