Making the Best of an Audio Transformer

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A discussion of the effect of the various characteristics of a transformer on its performance. Curves are shown for low- and high-frequency performance of both input and interstage transformers.

The previous articles have clarified the properties of audio transformers bearing on its performance, and shown how the electrical properties of an individual specimen can be measured up. To make the best use of this information, charts have been devised to simplify prediction of performance, and adjustment of circuit values for optimum.

In any audio circuit, frequency response is usually considered first. Generally it is desirable that this should be as flat as possible for as wide a frequency range as possible, but sometimes deliberate narrowing of the band or correction for deficiencies elsewhere is required. The charts here given enable any of these requirements to be met with the minimum of effort.

Low-Frequency Response

Treatment of this end of the spectrum falls into two groups, as explained in the first article:[1] (1) direct-coupled transformers, either single ended or push-pull; and (2) parallel-fed transformers.

The treatment for direct-coupled transformers is simple, as previously explained. The response is generally of the form shown in *Fig.* 3. of the first article (reproduced here as *Fig.* A), the 3-db point on this curve being found by equating the reactance of the primary inductance to the total shunt resistive impedance, consisting of the input impedance or plate resistance of the tube, in parallel with the referred secondary load resistance and the resistive component of magnetizing current. To adjust this l.f. cut-off frequency, any of these impedances, or the primary inductance, may be altered to produce the desired result. Plate resistance can be modified by the use of feedback. The load resistance may be fixed, but in some applications, such as input and interstage transformers, resistance shunted across the secondary is not regarded as a load, and may be adjusted to suit response requirements. The primary inductance can be modified by adjusting the air gap, or by altering the d.c. polarizing through the primary, in the case of single-ended interstage transformers.

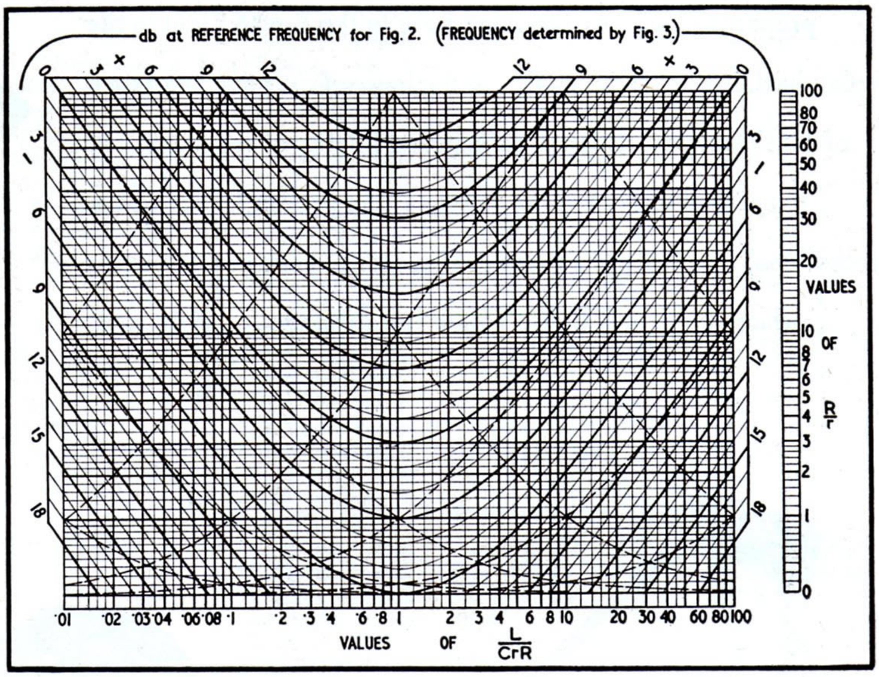

Fig. 1. Chart for determining response shaping from known values of L, C, r, and R (for significance of which see text); and for estimating effect of varying circuit values.

In direct-coupled transformers where d.c. polarizing is present, the inductance of the primary is reasonably constant, and the response curve follows the shape of *Fig.* A quite closely. But where there is no d.c. polarizing, and the transformer is cored up without an air gap, the primary inductance changes quite considerably with both amplitude and frequency, so the shape will not conform at all closely to this response. However, in these cases the l.f. response is usually made better than minimum requirements at all levels, so that its exact shape at any level is unimportant.

When using parallel-fed transformers the treatment is somewhat different. The l.f. cut-off network is analogous to a tuned circuit, and the shape of the response depends on the degree of damping present, series and shunt. Here again the primary inductance value is likely to vary with level and frequency, unless a component with a gapped core is used, so accurate prediction is rendered difficult. For this reason charts specifically for l.f. response prediction are not included, but those provided for h.f. response prediction are made adaptable for l.f. as well, where required. When using the charts for working out a suitable l.f. response, the frequency scale of *Fig.* 2 is reversed.

Although selection of conditions resulting in critical damping, or even a small degree of peaking, has been known, for the purpose of extending the l.f. range, it is not to be recommended for the reason that response will vary with signal level. On the other hand, when space or cost is restricted, it will be found that use of a coupling capacitor larger than an optimum value for critical performance, will deteriorate the l.f. response, rather than improve it.

High-Frequency Response

Variable inductances do not make the job so difficult at this end. Leakage inductance is constant, so quite accurate prediction is possible.

In *Figs.* 1 and 3, *r* always stands for the impedance connected to the low-impedance winding, and *R* for that connected to the high winding. So in step-up transformers, such as input or interstage, *r* is the input impedance or plate resistance in parallel with the coupling resistor, and *R* is the referred secondary shunt resistance.

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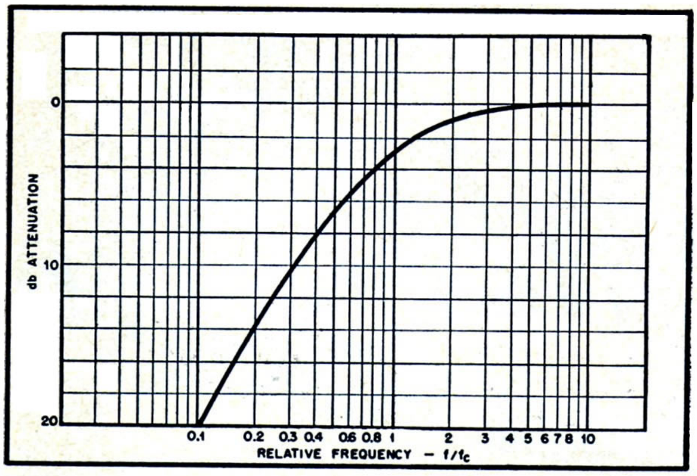
[1] N. H. Crowhurst, "How good is an audio transformer?" Audio Engineering, March, 1952.



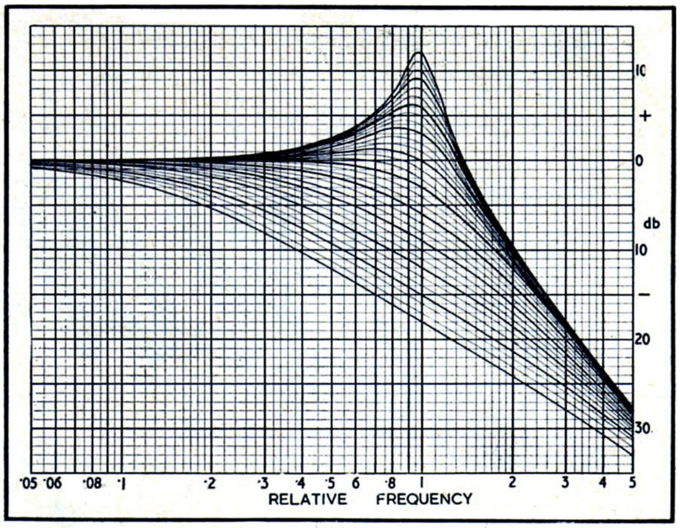


Fig. A. (above) Low frequency cut-off attenuation characteristic, 6 db per octave. Fig. 2. (right) Showing the possible variations of response shaping. The shape applicable to a particular case is determined by the Chart of Fig. 1.

To apply the charts to l.f. responses, r is the parallel combination of the tube plate resistance and its coupling resistor, and R is the parallel combination of all shunt resistance components *after the coupling capacitor,* referred to the primary.

Output transformers employ a step-down ratio, so R becomes the source impedance of the plate circuit, and r is the load resistance referred to the primary.

For h.f. circuits, L is the leakage inductance referred to the appropriate winding, and C is the total shunt capacitance "seen" by the high winding, including its own self-capacitance, referred to the same winding as everything else.

For l.f. circuits, L is the primary inductance, and C the coupling capacitor value.

To use the charts, values of r and R are assumed, L will be fixed by the transformer itself, and C will have a minimum value fixed by the transformer and its associated circuit. From these values the quantities L/CrR, R/r, and LC are evaluated (L in henries, C in farads, r and R in ohms). The chart of *Fig.* 1 is then used to locate the shape of the response among those shown in *Fig.* 2, and the chart of *Fig.* 3 locates its position on the frequency scale. The right half of *Fig.* 3 applies to h.f. cut-offs and the left half to l.f. circuits. *Figure* 1 finds the db response at the frequency given by *Fig.* 3, which is marked 1 on the RELATIVE FREQUENCY scale of *Fig.* 2. This reference frequency is the point on the curve at which the slope is downwards at 6 db/octave.

Explanation of the reason for choosing this reference frequency will help to clarify the information conveyed by the charts. An alternative presentation[2] uses the peak frequency as reference, where peaking occurs, and an imaginary equivalent where there is no peaking, the exception being the boundary case between the two regions, which has to be treated separately. This presentation has the advantage of providing precision prediction of any individual response more readily, because a "universal" curve representing each region can be drawn, which is interpreted by its own db conversion chart to suit all values within the region. Its disadvantage for the present purpose is that the reference frequency slides off the opposite end of the scale as the critical boundary condition is approached, i.e. it falls to zero for h.f. cut-offs and rises to infinity for l.f. cut-offs; this makes presentation of varying response with different circuit values obscure, if this reference is used. The use of the 6 db/octave slope reference point enables continuous presentation through both regions.

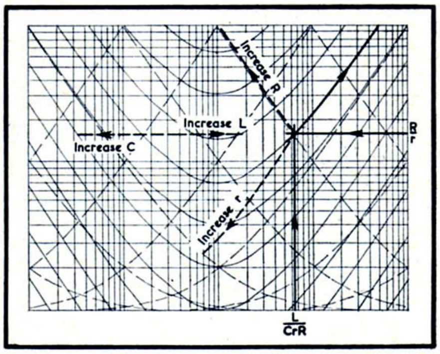


Fig. 4. Showing how the effect of changing circuit values is estimated by use of Fig. 1.

The 6 db/octave slope point is also the frequency at which phase delay (or advance in l.f. cut-offs) is 90 deg. The phase characteristic is always symmetrical about this point, and the amplitude response may also be regarded as centered about this point, if it is referred to a 12 db/octave cut-off at this same frequency, instead of to zero level both sides of cut-off.

Notice that the curve in *Fig.* 2 with zero level at the reference frequency has a peak of about 1¼ db at a relative frequency of 0.7; the – 3-db-at-reference-frequency curve is the critial or boundary case where peaking ceases; this is not quite the same as what is generally known as critical damping in connection with the introduction of transient distortion; critical damping, according to the accepted definition, is achieved by the – 6-db-at-reference-frequency curve.

The scales used in *Figs.* 1 and 3 have been chosen to assist accuracy in drawing. The R/r scale on *Fig.* 1 is based on the law $\log(1+R/r)$, which allows a template to be used for the db rulings. By adjustment of the L/CrR scale, straight db rulings could have been used, but the conventional log scale makes reading of L/CrR values easier. In *Fig.* 3 the scale for R/r is based on $\log(1+$

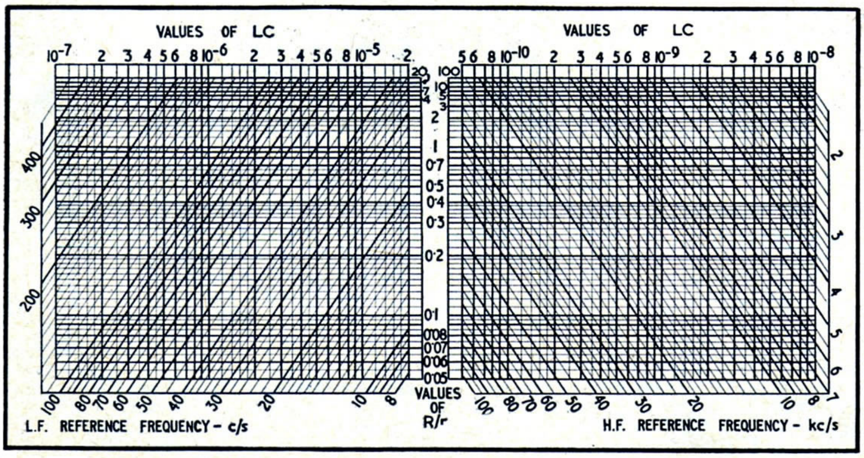


Fig. 3. Charts to determine the frequency location of the response predicted by Figs. 1 and 2. The left chart applies to l.f. cut-offs and the right chart to h.f. cut-offs.

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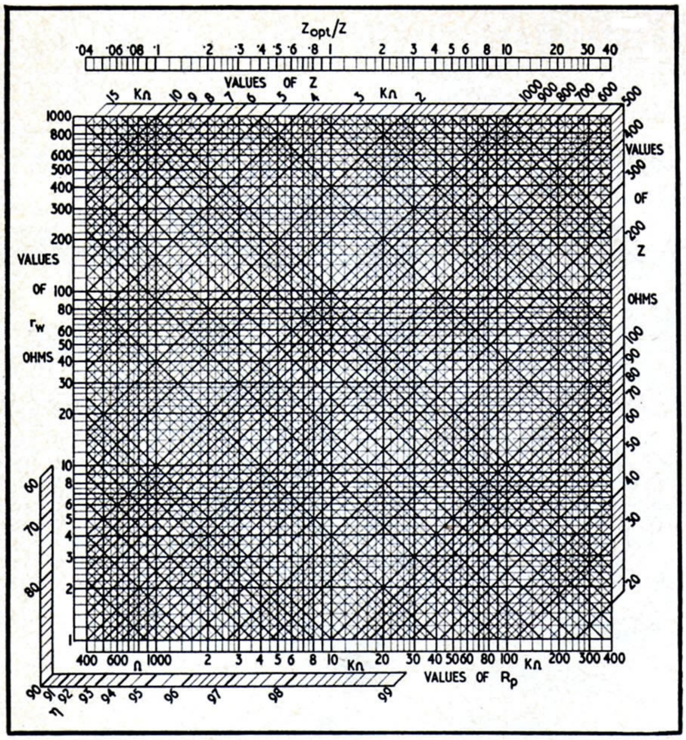
[2] *Electronic Engineering* (England) Nov. and Dec., 1951, and Jan. and Feb., 1952.



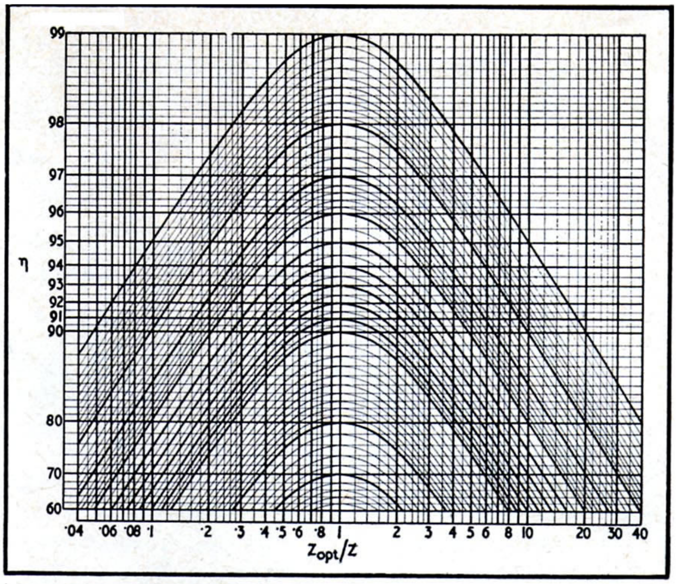


Fig. 5 (left). Chart to determine maximum efficiency, η, of a transformer, and the ratio of actual operating impedance to the impedance giving maximum efficiency. Fig. 6 (above). Chart applying the information from Fig. 5 to find the actual efficiency at the operating impedance.

r/*R*), allowing straight rulings to be used for frequency reference. Here the cramped spacing of the *R*/*r* scale toward the top gives an idea of the reduced effect on frequency when its value is large. The author has in preparation a book on the use of audio transformers, using charts with a different configuration again: a cut-out log scale can be applied to show the effect of variation in *R, r, L,* or *C* values more definitely; however, it was felt that this idea was not appropriate for a magazine article, so advantage is here taken of the construction yielding greater accuracy.

Adjustment of Values

Use of the 6 db/octave slope frequency as a reference does not mean that the frequency does not change at all as circuit values are altered, but that the change is easier to visualize or assess. If either $r = 0$ or $R = \infty$ (the former never occurs and the latter seldom), variation of the other value would change the response in the way shown at *Fig.* 2 without changing the reference frequency. Values of *R* and *r* such that both contribute to the damping push the reference frequency upwards for h.f. circuits or downwards for l.f. circuits, to the degree indicated by the chart of *Fig.* 3. Variation of *L* or *C* will change the reference frequency in inverse proportion to the square root of their value, the chart of *Fig.* 3 again being used to calculate this.

Figure 4 shows how the chart of *Fig.* 1 may be used to visualize or estimate the effect of changing circuit values. The dotted lines on *Fig.* 1 represent a condition where *L, C* and either *r* or *R* are maintained constant, while the fourth quantity is varied. *Figure* 4 shows clearly the direction of movement along these dotted lines (or parallel with them) for increasing values of *r* and *R* respectively—decreasing values naturally produces movement in the opposite directions. Increasing *L,* or decreasing *C,* moves the reference point horizontally to the right, and increasing *C,* or decreasing *L,* moves it to the left.

In h.f. circuits, *L* is set by leakage inductance, but *C* can be increased by the addition of shunt capacitance across the high-impedance winding. In l.f. circuits, *L* may be variable by adjustment of the gap, and definitely does vary with signal level; *C,* the coupling capacitor, can be made any desired value.

No provision is made on the chart of *Fig.* 1 for $R = \infty$. In cases where a step-up transformer may be working without a secondary loading resistor, a high value may be assumed. It will be noted that the dotted lines representing variation of *R,* with other values constant, converge to become parallel with db rulings towards the top left hand corner of the chart. A high value of *R* will produce a reading in this area, where its precise value will not appreciably affect the db reading.

Efficiency

In transformer circuitry, insertion loss is more readily dealt with in terms of efficiency. Percentage efficiency can easily be converted to db insertion loss by log table, slide-rule, or one of the ready made conversion tables frequently published. Efficiency relates to power transfer—and not voltage transfer—so for example, an efficiency of 60 per cent is an insertion loss of 4 db, 90 per cent

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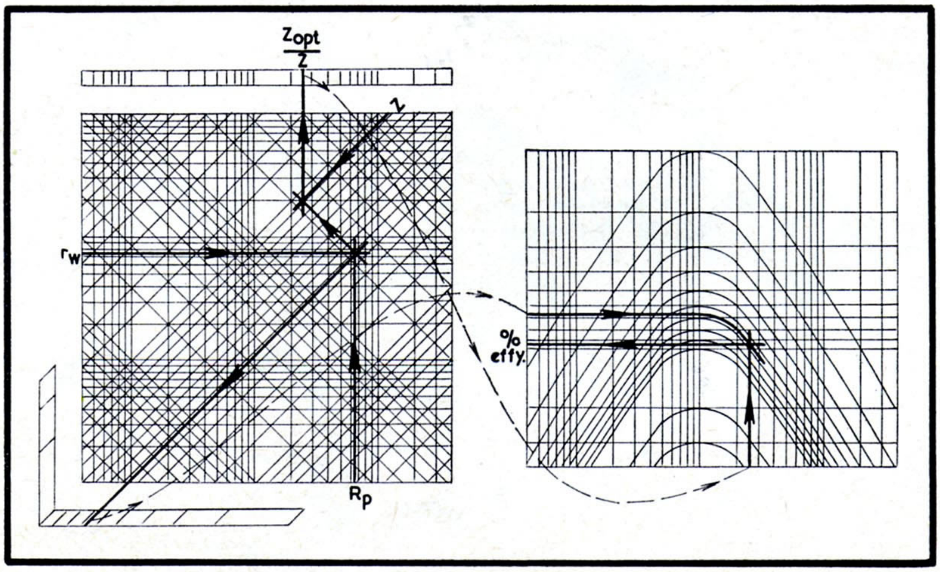

Fig. 7. Showing how the charts of Figs. 5 and 6 are used to find the efficiency of a transformer.

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represents 2 db, and 99 per cent represents 0.23 db.

The use of the charts in *Figs.* 5 and 6 to determine efficiency is illustrated by *Fig.* 7. *Figure* 5 is used to find the maximum efficiency of which a transformer is capable, and the relation between the actual operating impedance of the transformer and that producing this maximum. *Figure* 6 then gives the actual efficiency from this information. r_w is the total winding resistance referred to the winding chosen for making the calculation; R_p is the shunt loss due to the core, referred to the same winding, and measured at a mid-frequency of, say 1000 cps. (Although somewhat lower frequencies are often taken for mid-frequency for other audio purposes, 1000 cps gives a fairer picture for audio transformer efficiency). An impedance which is the geometric mean of r_w and R_p results in maximum efficiency, and this maximum efficiency is given by the η scale on *Fig.* 5. At the same time, reference in the manner shown in *Fig.* 7 gives a value of Z_{opt}/Z, indicating by what ratio the actual impedance, Z, at which the reference winding is operating, differs from Z_{opt}, which gives this maximum efficiency.

The maximum efficiency point is not always the best impedance at which to work a transformer, because frequency response must be considered as well, and in smaller models harmonic generation may also affect the consideration.

Having found what the efficiency is for one particular impedance, the construction of the charts avoids the necessity for going through the whole procedure again for another impedance; the efficiency for the new impedance may simply be read off from a different point on the same curve of *Fig.* 6.

Harmonic Generation

This is a relatively simple calculation, so no special chart has been provided for it. The previous article gave a method of measuring harmonic content as a percentage of fundamental magnetizing current. Magnetizing current at the frequency and amplitude concerned can be expressed as a shunt impedance referred to the primary. The source impedance and load impedance referred to the primary can also be expressed as a combined shunt impedance. To find the effective harmonic percentage generated, the percentage measured is then divided by the ratio between the shunt impedance due to magnetizing current and that due to external circuit impedances. For example, if the measured percentage is 15 per cent, the shunt impedance due to magnetizing current 50,000 ohms, the plate resistance 20,000 ohms, and the referred load resistance 5000 ohms: the external shunt impedance is 4000 ohms, and the effective harmonic generation. $\frac{15\times 4}{50} = 1.2$ per cent.

Input Transformers

Insertion loss in an input transformer is usually unimportant compared with its frequency characteristic and other properties. It is normally direct coupled, but with no d.c. polarizing. Due to low signal levels, working flux densities in the core are extremely small, and the effective primary inductance varies over a considerable range with variation of signal level. Inductance should be sufficient to maintain good response, even with its smallest value. If it is not sufficient to do this, the only remedy is to reduce the working impedance by additional shunt resistance, which will also add insertion loss—at a point it can ill be afforded; so generally a compromise is necessary, or a better transformer.

Its h.f. response is generally determined as to range by the impedance to which the source is matched by its step-up, and the input capacitance of the tube it feeds. Sometimes an h.f. peak appears, as will be shown by use of *Fig.* 1. In such cases increase in input capacitance pulls down the frequency of peak, but usually increases its height; the best remedy is an appropriate value of shunt R across the secondary. If this restricts the range more than is desired, tube input capacitance must be reduced as well, by the use of a little inverse current feedback (leaving off the cathode by-pass capacitor). The only alternative is another transformer with less step-up.

If the whole chain has a deficiency in highs that can be corrected by peaking, the input transformer is a good place to introduce such correction, because it will boost the highs in the signal before the thermal noise of the first stage is added to it.

Shielding against hum pick-up is not one of the properties within the scope of this article, but it is important for some input transformers, and so should be mentioned. Some reduction can always be effected by orientation, but if shielding is totally inadequate the only answer is a better shielded job.

Interstage Transformers

Direct-coupled types carrying d.c. polarizing usually have larger leakage inductance and self-capacitance than types without provision for d.c. polarizing. If low frequencies are deficient, the best remedy is to shunt the primary with a suitable resistor. This will bypass some of the polarizing current, thereby increasing inductance slightly, and at the same time reduce effective source impedance. But this shunt resistance may produce a peaking effect in the h.f. response. As with input transformers, this may be overcome by suitable shunt resistance across the secondary. The charts can be used to find the best combination more readily than protracted trial and error, taking a frequency run each time a change is made.

Parallel-fed types of interstage transformer may cause peaking at one or both ends of the audio spectrum. In general it is best to avoid peaking at the l.f. end, aiming at a value of L/CrR greater than unity, so that variation of inductance with level produces a minimum variation in response. However, going too far in this direction may restrict the l.f. range more than is desired; so the charts may be used to find the best compromise, using two different values of inductance (extremes of variation with level) to see what effect signal level can have on response.

The h.f. end will be easier to handle, because with most parallel-fed components there is more in hand. The limit to step-up is generally set in the same way as for input transformers.

Some points should be noted here that help in getting just the right effect at both ends of the spectrum at once. Resistance across the secondary has the effect of reducing tendency to peak at both ends, although maybe in different degrees, according to relative values of L/CrR for each end. Varying the coupling resistor also has a similar effect at both ends, but possibly different in degree. Usually if the secondary shunt resistor has more effect at one end, the value of coupling resistor will have more effect at the other. But a resistor in shunt with the *primary* (after the coupling capacitor), has opposite effects at each end: at the l.f. end it is the same as an equivalent referred value shunted across the secondary, and so reduces the tendency to peak; but at the h.f. end it shunts the source resistance, reducing the value of r, so increasing the tendency to peak.

Thus adjustments of coupling resistor, coupling capacitor, shunt primary resistor, and shunt secondary resistor, afford a considerable variety of possibilities with the parallel-fed type of interstage transformer. Exploration of these possibilities to find the best combination can be greatly expedited by use of the charts.

Output Transformers

In output transformers everything takes on different proportions. The transformer is step-down, and most circuits—even using tetrode or pentode outputs (inverse voltage feedback being invariably used)—have an effective plate resistance that is but a fraction of the referred load resistance; so peaking at h.f. is impossible. Instead, harmonic generation and efficiency are now the features to watch. If harmonic generation at the lowest frequency of interest is kept low, l.f. response also will usually be taken care of. The charts in *Figs.* 5 and 6 will be useful in working out efficiency, particularly to determine whether a transformer designed for operation between, say, 7000 and 5 ohms, will serve satisfactorily between 10,000 and 7 ohms, or between 5000 and 3½ ohms.

The remarks here made about output transformers also apply to loudspeaker and line-matching transformers.