Transformer Distortion

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In two parts—Part 2

The causes of distortion in transformers are fairly well known to transformer engineers, but there is little the user can do to avoid it. However, a thorough understanding of the parameters which cause distortion and the effect of core material, size, stacking, and operating conditions will help engineer and experimenter alike in their choice and use of transformers.

THE CORE MATERIALS discussed have all been suitable for use in output transformers by virtue of high saturation flux densities. The silicon steels saturate at about 20,000 gauss, the 50% nickel iron at about 16,000 gauss.

Another material of importance is known as Mumetal.[8] It is not useful in output transformers, saturating at 8,000 gauss, but is superior at lower flux densities, having the highest permeability of the lamination metals. It is the most expensive and the most fragile, but in a core completely free from air gaps, it has initial and maximum permeabilities 2 to 4 times as great as 50% nickel iron measured in the same form.

The Mumetal curves of *Fig.* 4 are not directly comparable with the first three figures because the core is very much smaller and the impedance relations are different. This transformer was designed for line matching. It is the small size sometimes enclosed in microphone cases. It was measured with one winding driven by a source of rated impedance and the other winding unloaded. This is not the design condition for a line matching transformer, but in the ordinary case where the gain controls follow the first stage of amplification, the line transformer is generally followed by an input transformer and the source is the only loading resistance. This is the condition that was approximated.

The Mumetal distortion curves, *Fig.* 4, are very similar in shape to the 4750 curves of *Fig.* 3 except for an 8,000-gauss saturation point instead of 16,000 gauss. This reduces the power-handling capacity to one fourth that of the 4750 alloy, precluding output transformer use. By coincidence, the low-level distortion of the Mumetal is the same as for the 4750 alloy. This is because of the difference in test conditions. If this Mumetal had been measured in the EI-75 laminations of *Fig.* 3 the permeability would have been about twice that of the 4750 alloy. The transmission loss in decibels would have been about half as great as *Fig.* 3 and the distortion about half as much as *Fig.* 3 at low levels. At high levels the Mumetal also produces about half as much distortion as the 4750 if compared at half the flux density of the 4750, due to the 2 to 1 ratio of saturation flux densities. The advantage of Mumetal diminishes at higher levels. It is not often used above 2,000 or 3,000 gauss.

It must be remembered that production variations for high-permeability materials are large and cause corresponding variations in transformer characteristics.

The distortion of *Fig.* 4 is the actual distortion produced by the transformer at 25 cps when used in the usual manner. The distortion is much too high for a good-quality sound channel, despite the Mumetal core. To reduce the distortion the energizing current must be reduced. One approach is added turns on the coil, but this means finer wire and higher resistance loss. A larger core is a more satisfactory solution. If the original coil resistance is duplicated, the larger transformer has higher impedance and reduced distortion.

Figure 7 is an example of a large transformer with a Mumetal core. The maximum low-level distortion is about 0.4 per cent third harmonic. This is much improved over the 3 per cent third for the small transformer. To accomplish this improvement, along with improved low-frequency response, and greater power-handling capacity, the core of this transformer weighs 40 times as much as the core in the small transformer.

A line-matching transformer used in an instrument was required to be nearly distortionless. The measured low level distortion peak was 0.08 per cent third harmonic at 20 cps. The core of Mumetal weighed 33 pounds. This huge core was unavoidable if this low distortion level at 20 cps were to be attained. Actually a really good power amplifier has as low distortion at 20 cps as this one transformer. This immense, very expen-

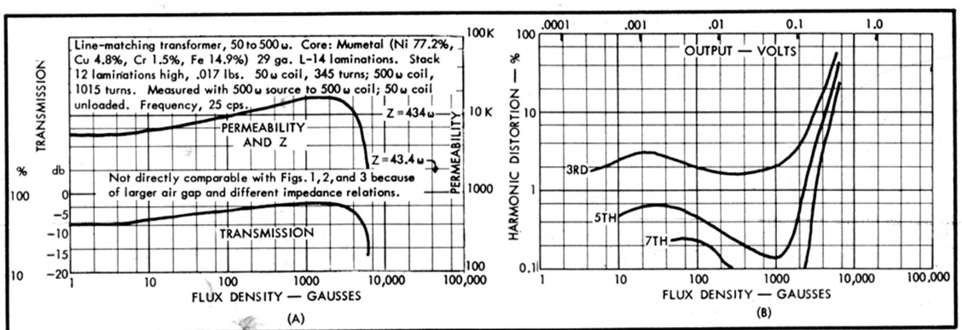

Fig. 4. Curves of transmission, permeability, distortion, and impedance vs. flux density for Mumetal core material.

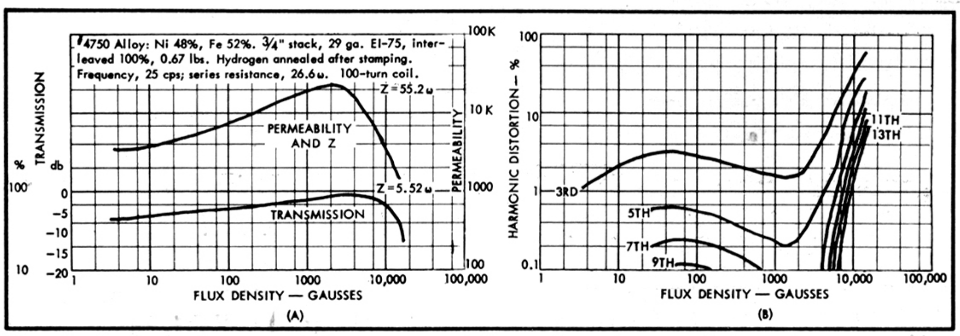

Fig. 3. Curves of transmission, permeability, distortion, and impedance vs. flux density for No. 4750 alloy core material.

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[8] Bulletin EM-16, *"Allegneny Mumetal."* Allegneny Ludlum Steel Corp., Brackenridge, Pa.

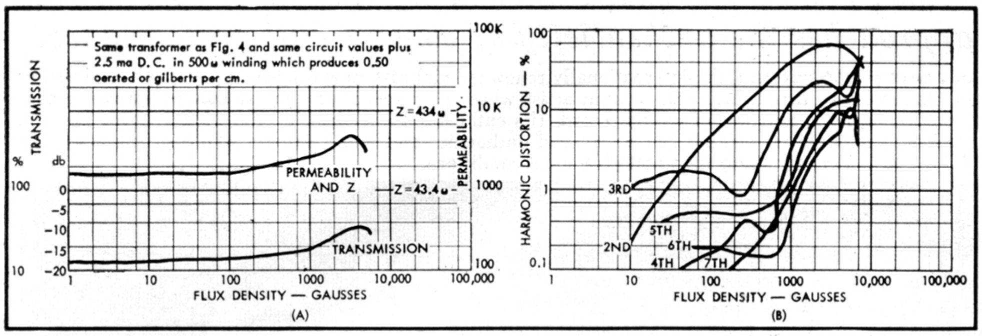

Fig. 5. Curves of transmission, permeability, distortion, and impedance vs. flux density for Mumetal core with d.c. polarization.

sive transformer illustrates how nearly impractical is a distortionless transformer.

The disparity in variations of amplifier and transformer distortion with level is an important consideration. Amplifier distortion is measured at maximum power and usually drops rapidly with reduction in signal. As a result, the amplifier in use contributes very little distortion most of the time. In contrast, a line transformer functioning over the range from a few gauss to a few thousand gauss, distorts at all levels, and in use distorts all signals at low frequencies.

Direct Current Polarization

The effect of direct current in a transformer is intricate but will be briefly considered. Audio transformers are never required to carry direct current when this can be easily avoided, but an output transformer must usually carry the direct current for its stage. In the case of push-pull circuits, the direct current largely balances in the transformer, subjecting the core only to the unbalance current. This can be made negligible and is generally ignored in transformer design. In a single-ended power-output stage the direct current is equal to the largest alternating currents, excepting overload, and profoundly limits the low-frequency capability of the transformer. With alternating currents alone, the core material contains no flux at no signal. With sine wave excitation the core will saturate at the same signal level with either instantaneous signal polarity. In contrast, direct current biasing adds to one polarity of alternating current and subtracts from the other polarity, so that the core saturates first in the direction of additive currents. Consequently direct current polarization reduces the power handling capacity of the core, because a part of the magnetization range is no longer utilized. Another consequence is a reduction in alternating current permeability, due to partial saturation of the core. If the transformer is constructed with an interleaved core providing a minimum air gap and is tested both with and without direct current, in the usual case the transformer core is nearly saturated by the amount of direct current required by the amplifier stage. Therefore the inductance is drastically reduced. A partial remedy is an increased air gap. The air gap regrettably adds to the reluctance of the magnetic path, but it reduces the direct current magnetization of the core material. With substantial direct current polarization, the added reluctance of the air gap will be more than offset by the decreased reluctance of the core material, providing a net increase in inductance.

The transformer of *Fig.* 4 is a size now in use with transistors. In transistor circuits, direct current is usually carried by the transformer. *Figure* 5 is of the same transformer carrying 2.5 milliamperes of direct current. With the direct current polarization, the low-level alternating current permeability with Mumetal is about twice as great as with silicon steel, and about the same as with 4750 alloy. Calculating the proper air gap with the direct current present[9] results in a figure of .0004″ compared to the actual .000128″. The next larger gap commonly used is the butt gap which produces a minimum air gap on the order of .003″ with small laminations. One intermediate gap size could be produced by interleaving the laminations two by two, instead of one by one. This should double the air gap, because only half as much lapped surface would be available. Gaps smaller than the butt gap could be produced by coating the laminations with insulating coatings of proper thickness and interleaving them. This is awkward and certainly not in general use.

The .000128″ gap in this core, although smaller than optimum, was not altered. Thus the result of added direct current is not obscured by other changes.

Direct current polarization adds the even numbered unsymmetrical harmonics to the odd numbered symmetrical ones produced by alternating current alone. The result, *Fig.* 5, is a horribly full harmonic spectrum. Beside the addition of the even-numbered harmonics, the total distortion is very much greater at all flux densities above 100 gauss. The cause of this excessive distortion is the asymmetry of polarized core material which responds differently to the two polarities of signal, and the reduced transformer impedance which impresses a larger part of the core distortion on the circuit.

The permeability, *Fig.* 5, with the polarization is quite different from the unpolarized permeability, *Fig.* 4. At low flux densities the permeability is determined by the d.c. polarization, while at the highest flux densities the polarization has slight effect. In this case the low level permeability is reduced from 6000 to 1600. This approximate ratio holds up to about 2500 gauss, while the permeability is only slightly reduced at 6000 gauss. This reduction in low and moderate level permeability raises the low-frequency cutoff in the same ratio, as for example from 40 to 150 cps.

An output transformer for a 6V6 was designed on the core of *Fig.* 1, using the same material, Audio A silicon steel. The low-level inductance, with the proper .007″ air gap, was 0.3 as great as the inductance without d.c. and without an air gap.

With single-ended audio output transformers of ordinary size, an inductance decrease by a factor of three due to the direct current and the appropriate air gap, seems typical. In the region of maximum permeability the decrease is greater. To compensate completely for this handicap, a much larger transformer would be required. Even so, a large part of the even-numbered harmonic distortion would remain. Direct current is thoroughly undesirable in audio transformers.

Core Insensitivity to Frequency

The impedance of a coil is proportional to frequency, but the permeability and distortion generation of core materials are largely unaffected by moderate frequency changes. To verify this, Audio A was tested first at 25 cps, then at 100 cps. Impedances were adjusted to the same relative values at each frequency. Both at 55 gauss and at 10,000 gauss, the permeability and distortion decreased less than one part in 20 due to this large frequency increase. Eddy current losses, which act as a distortionless shunt, increase with frequency, causing these small permeability and distortion reductions. Higher permeabilities are more frequency dependent, but for all practical purposes the core characteristics measured at 25 cps apply to any low audio frequency.

Distortion Variation with Frequency

Figure 6 indicates the variation of transformer characteristics with fre-

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[9] *"Magnetic Core Materials Practice,"* pp. 68–88. Allegheny Steel Company, Brackenridge, Pa.

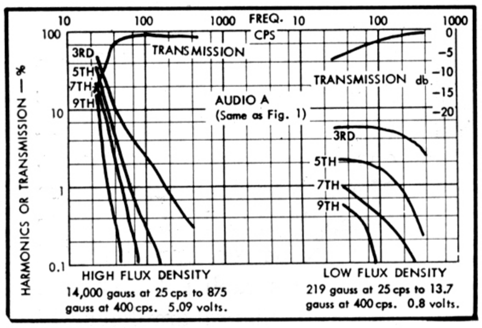

Fig. 6. Curves showing transmission and distortion on Audio A core material at both high and low flux densities.

quency at constant voltage, or flux density inversely proportional to frequency. This is the usual situation in audio equipment. At high flux densities the permeability increases with frequency, at low flux densities it decreases with frequency. High series resistances were used in these measurements. They can be applied to lower circuit resistance applications by simple calculations.

The high-flux-density curves, 14,000 gauss at 25 cps, approximate the flux density in a small, inexpensive push-pull output transformer. At 25 cps the transmission is 0.20 and the third harmonic is 59 per cent. At double the frequency the transmission is 0.80 and the third harmonic is 14.5 per cent. The higher harmonics drop even more abruptly. This very rapid improvement results from a permeability increase with frequency accentuating the increasing inductive reactance.

The low-flux-density curves, 219 gauss at 25 cps, typify input transformer operation. Doubling the 25-cps frequency moderately increases the transmission from 0.45 to 0.60 but only slightly decreases the third harmonic from 5.4 per cent to 4.5 per cent. The frequency effect is small because the increasing inductive reactance is diminished by the decreasing permeability.

The two parts of *Fig.* 6 are indicative of the most rapid and least rapid change of characteristics with frequency likely to be encountered.

Other Audio Core Materials

Beside the core materials previously discussed, others should be mentioned. The prospect for a material with a much higher saturation flux density is very poor. The best very-high-flux-density material now available is an alloy of cobalt and iron, Permendur or Hiperco,[6] which saturates at nearly 24,000 gauss. This material is very difficult to fabricate and very expensive. It has not been used extensively in transformers. A related material, Supermendur, has the same high saturation point combined with lower core losses at very high flux densities than any other material. It would be useful in high-level audio transformers except for a rectangular hysteresis loop which makes it extremely non-linear.

Ferrites are magnetic oxides which have very high volume resistivity, allowing the use of solid cores without excessive eddy losses. They are widely used at frequencies above the audio spectrum, but practically unused at audio frequencies because of low permeability and limited power-handling capacity.

Many special core materials are used for such applications as high-storage-factor inductances and magnetic amplifiers. They are generally unsuited for audio transformer use. Perminvar and Conpernik have nearly constant permeabilities at low levels, and are used in precision inductances. Deltamax, Square Permalloy, and Supermendur have rectangular hysteresis loops especially advantageous in magnetic amplifiers. Cores of compressed powdered Molybdenum Permalloy or iron are used in low loss coils at audio and higher frequencies, but have no particular merit in audio transformers, because of low permeabilities.

Supermalloy

The lowest distortion and the highest permeability at low levels is produced by Supermalloy,[10] a nickel-iron alloy with additional ingredients. It is not suitable for laminations due to the limitations on very high permeabilities imposed by air gaps, and because the material is highly sensitive to mechanical strain. It is produced in tape form and wound into gapless toroids. Coils for such transformers must be wound by hand or by toroid winding machines. This material is used when the ultimate in performance is required. It has an initial permeability of at least 45,000 and a maximum permeability of several hundred thousands. These figures are several times as high as those for good Mumetal. The saturation flux density is about 7500 gauss, similar to Mumetal, but the permeability peak is near 4500 gauss in contrast to a peak near 2000 gauss for Mumetal. Supermalloy accordingly retains its desirable properties to higher levels than Mumetal.

A large Supermalloy core yielded far the lowest distortion measured. The very high permeability would cause this, but additionally the magnetization curve is more linear than the curves for the lamination metals, further reducing the distortion. Measured under conditions equivalent to *Figs.* 1, 2 and 3 the third harmonic was .08 per cent at 22 gauss, 0.18 per cent at 27 gauss, 0.26 per cent at 1085 gauss, and 0.48 per cent at 5210 gauss. There was no low level distortion peak. Due to the high permeability and resultant high impedance the transmission was 99 per cent even at initial permeability. The cost of this transformer was several hundred dollars.

Supermalloy will not generally displace Mumetal in low level transformers. It is superb core material but it is too difficult to use and too expensive.

Useful Relationships

When the physical constants of a transformer are known, the distortion can be determined from these curves by making allowance for the relative circuit impedances.

Even with nothing but the transformer terminals available, useful distortion information can be deduced. Comparison of the distortion and permeability curves of *Figs.* 1 and 3 shows remarkable similarity in shape, not absolute value, although the materials are very different. Even *Fig.* 4 for Mumetal has similarly shaped distortion curves. The permeability curve for Mumetal measured with a small air gap is also similar in shape to *Figs.* 1 and 3. The measurements on low-grade silicon iron laminations showed the same similarity. Excepting grain oriented material, *Fig.* 2, which is not in lamination form, the distortion produced by high-level lamination materials depends on flux density and circuit impedances, and is largely independent of the type of core metal.

If the transformer impedance curve is plotted at a constant frequency and variable voltage, the point of highest impedance is the peak of the permeability curve and can be referred to *Fig.* 1 for example, to determine distortion. (If the core were grain oriented silicon, the shape of the impedance curve would immediately identify it. The peak would be broader, and closer to the saturation point, and the slope would increase at low flux densities, rather than decrease as with the lamination materials.)

Measurements of the distortion components of the energizing currents were

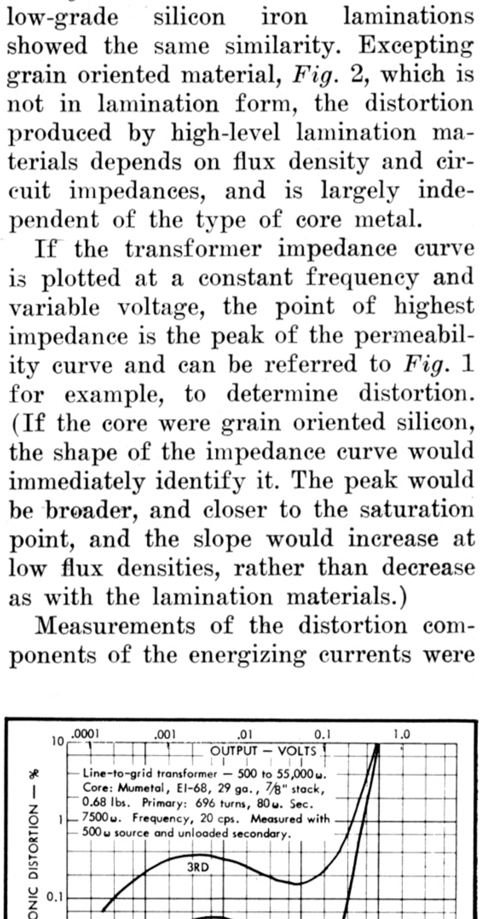

Fig. 7. Curves showing distortion vs. flux density for low-level input transformer with Mumetal core.

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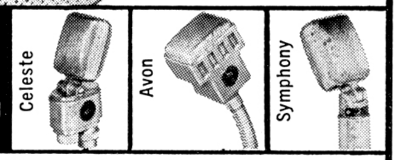
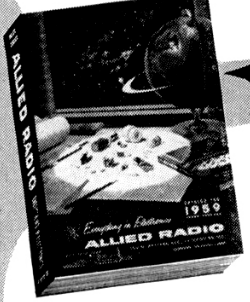
[6] *"Westinghouse Metals and Alloys,"* Westinghouse Electric Corp., East Pittsburgh, Pa.

[10] Bulletin TC-101A, "Properties of Deltamax, 4-79 Permalloy, and Supermalloy." Arnold Engineering Co., Marengo, Ill.





TRANSFORMERS

(*from page 46*)

made for these several core materials. A pure sine-wave voltage was produced across the coil while the corresponding distorted energizing current was analyzed. To accomplish this, the transformer was included in a negative feedback loop with a very large feedback quotient from an unloaded winding on the transformer. This maintained an exceedingly pure sine-wave flux-density variation. The energizing current was passed through a resistor. The voltage across this resistor, being proportional to energizing current, was analyzed. Measured in this way, the distortion in the energizing current depends only on the core material and the flux density. These measurements were restricted to high flux densities by amplifier noise and related problems, so that complete curves could not be obtained. The high-level comparisons thus made are very helpful. In *Figs.* 1 and 3 the permeability peak occurs at 3500 or 4000 gauss. The energizing currents at 3500 gauss for Audio A silicon steel, low-grade silicon steel, and 4750 nickel alloy respectively contained 16.3, 15.5, and 13.0 per cent third harmonic. This is a rather small variation and indicates that distortion calculation at the permeability peak as determined by impedance measurements alone, without knowledge of the core material, would generally be reasonably accurate. At high flux densities the distortion varies rapidly with changing level, reducing the accuracy of such comparisons. Distortion produced in vacuum tubes does not usually agree with calculated values, or published values, much more closely.

Curiously, the distortion at the low-level peak equals the distortion at the permeability peak for these lamination materials. The maximum low level distortion for Audio A, *Fig.* 1, is about 10 per cent third harmonic. At 4000 gauss, the permeability peak, the third harmonic is again about 10 per cent. This relation is also found in 4750 alloy and Mumetal. Also the low-level distortion peak in each case is at roughly one hundredth the voltage of the permeability peak. Having determined the voltage at which the impedance is maximum, and knowing the relative impedances of transformer and circuit at the permeability peak, the distortion at any flux density can be estimated. The accuracy will be best at low flux densities because those portions of the distortion curves are nearly flat. These relations do not hold for grain oriented tape cores which have distinctly different permeability curves.

To compare transformers designed for the same application, simply measure the energizing currents at the voltage and frequency of interest. The distortion ratio is very likely to be about the same as the ratio of energizing currents. In the case of output transformers it is most unlikely that the distortion ratio will be less than the energizing current ratio, but it may possibly be greater. The transformer with lower energizing current is likely to have more turns or a larger core. In either case the flux density will be lower, further reducing the distortion at high voltage levels. With low-level transformers the exact flux density has little effect on the distortion, and the accuracy of this simple comparison will be better.

High-quality low-level transformer cores are generally a material similar to 4750 or Mumetal. Transformers designed to handle the same amount of power, using either of these materials, can be compared on the basis of energizing currents alone with particularly good accuracy because the respective distortion curves are so very similar in shape. The difference in saturation points does not enter this comparison if the transformers actually handle the same amounts of power.

In choosing transformers, the heaviest or largest is likely to have the best low-frequency characteristics in the usual case where the core materials are similar. Core material and copper account for much of the transformer cost. Additional material is not intentionally used unless it provides a commensurate improvement in the transformer. Of course a large case sometimes contains a small transformer.

Transformers Preferably Avoided

Because audio transformers introduce amplitude and frequency distortion and waste power, they should be avoided when possible. It is not unusual for the elimination of one transformer to make a noticeable improvement in sound quality.

Certain transformer types are particularly objectionable. In designing a high-impedance transformer, high-frequency considerations limit the amount of inductance which can be provided. High-impedance audio transformers depend on properly damped resonances to extend the high-frequency range. An increase in coil turns or coil sizes reduces the frequency of these necessary resonances and thus reduces the high-frequency span. Therefore the more difficult the high-frequency problem, the more the low-frequency response suffers.

Of the common transformer types, the most undesirable from a distortion standpoint is the high-level interstage transformer. The secondary impedance must be high to develop sufficient grid swing and the power level is high, further increasing the low-frequency distortion. The available transformers for driving large triodes without grid current usually produce as much low-frequency distortion as the power tubes.

Input transformers are not quite as severe a design problem and the low-frequency response and distortion are somewhat better.

Line-matching transformers pose no difficult high-frequency response problem and accordingly produce the least low-frequency distortion.

The output transformer in a multigrid power stage generates several times as much distortion as an equivalent transformer in a triode output stage. This is because the circuit resistance across which the transformer develops distortion is much lower with triodes. If the output stage is single ended, polarizing the transformer core with direct current, the low-frequency transformer distortion will be particularly severe.

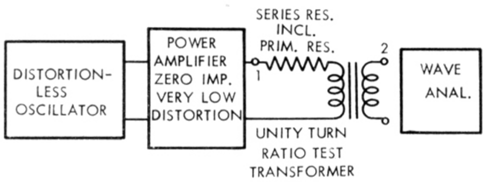
Negative feedback so effectively reduces distortion that output transformers should not be used without it. With large feedback factors, output-transformer distortion can be reduced to a negligible level.

The ear is relatively insensitive to the lowest audible tones. This attenuation of the fundamentals effectively emphasizes the distortion. It follows that accurate sound reproduction requires especially low distortion in the bass region where all transformers are least satisfactory.

When transformers cannot be avoided, only the best should be used.

APPENDIX

Transformer Formulas



$$\beta = \frac{E \times 10^8}{4.44\, f\, NAK} \qquad H_o = \frac{1.256\, NI}{l}$$

$$L = \frac{1.256\, AKN^2\, \mu_a\, 10^{-8}}{l} \qquad Z = 2\pi f l$$

$$\mu_a = \frac{L\, l\, 10^8}{1.256\, AKN^2} \qquad \mu_a = \frac{\mu_{ac}}{1 + \frac{\mu_{ac} a}{l}}$$

β = the peak flux density in gausses per square centimeter.
E = the r.m.s. sinusoidal voltage across the coil.
f = the frequency in cycles per second.
N = the number of turns in the winding.
A = the cross sectional area of the magnetic core in square centimeters.
K = the stacking factor or the fraction of the core cross section that is actually core metal. (about 0.88 with interleaved laminations)
L = the apparent inductance in henries.
μ_a = the apparent alternating current permeability of the assembled core.
l = the total length of the magnetic path in centimeters.
H_o = the polarizing force resulting from direct current in the winding, expressed in gilberts per centimeter or oersteds, applicable only with no air gap.
I = the direct current in amperes.
μ_{ac} = the actual alternating current permeability of the core material.
a = the length of the air gap in centimeters, assuming equal cross-sectional areas of air gap and magnetic material.
Z = the apparent impedance of the coil in ohms.

Distortion Comparison

$$R_t = \frac{b^2 R_s R_l}{b^2 R_s + R_l} \qquad \frac{D_t}{D_c} \cong \frac{R_t}{\sqrt{R_t^2 + Z_s^2}}$$

$$Z_s = b^2 Z_p$$

R_s = the alternating current source resistance.
R_l = the alternating current load resistance.
b = the ratio of secondary to primary turns.
$b^2 R_s$ = the source resistance referred to the secondary.
R_t = the total alternating current circuit resistance referred to the secondary.
$\frac{D_t}{D_c}$ = the fraction of the distortion generated in the core that appears on the secondary terminals.
Z_p = the primary impedance of the transformer at the fundamental frequency.
Z_s = the secondary impedance of the transformer at the fundamental frequency.

Test Arrangement

Wave analyzer connected to 1 and 3 to measure input voltage and check source distortion.
Wave analyzer connected to 1 and 2 to measure voltage across total series resistance including primary coil resistance.
Wave analyzer connected to 2 and 3 to measure net voltage across inductance and to measure harmonic distortion.

At all times the harmonic content of the entire measuring system was much lower than the harmonics generated in the test core. The third-harmonic voltage, which is of prime importance, was lower in the input signal by a voltage ratio of about 100, or 40 db, than the third-harmonic voltage generated in the test core. Under the worst conditions, for only a few of the hundreds of measurements involved, the voltage ratio for the higher harmonics was as poor as 1 to 10, or 20 decibels below the harmonic level generated in the test core. Æ

60-WATT AMPLIFIER

(from page 40)

metal film resistors. The author has been most satisfied with the quality of Nobeloy and the new Corning Glass metal film resistors, and both seem superior to deposited carbon types for audio work. However, these expensive resistors are required in the feedback circuit, on the 5879, and in the cathode of the output tubes only, for no measurable advantage can be ascertained from their use in other parts of the circuit, provided good quality carbon resistors are used.

There is but one eternal admonition for a home constructor, and that is to