Distortion in Transformer Cores

PART III.—DC POLARISATION : INTERMODULATION EFFECTS : CHOICE OF CORE MATERIALS

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THE basic cause and nature of iron distortion in output transformers have been discussed in the two previous instalments. This article deals with the secondary effects that have to be considered before a reasonably complete understanding of the subject can be claimed.

THE examples considered so far have all assumed a resistive load on the transformer and also that the anode currents of the push-pull valves were accurately balanced, so that the core was not polarised. In addition, only one grade of magnetic material has been examined analytically.

A loud speaker does not behave so conveniently as a resistance when constituting an output load. A resistance maintains the same ohmic value at all frequencies,

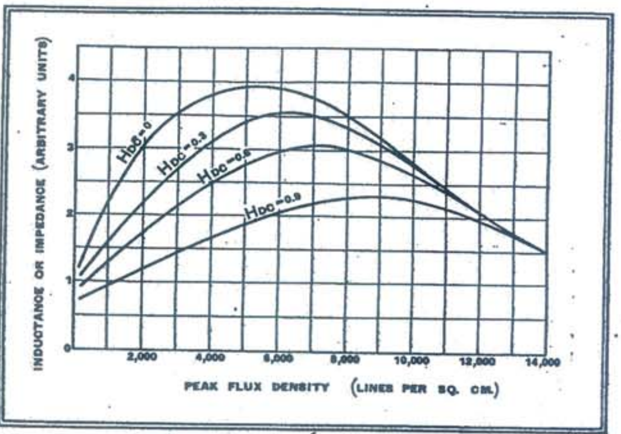

Fig. 17.—The relative inductances of a transformer with varying degrees of polarisation are shown for all values of B. The core material in this case was Silcor 2.

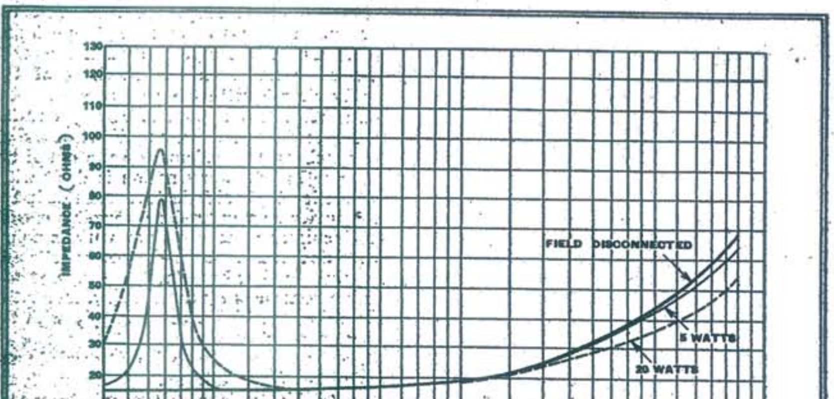

Fig. 16.—The impedance of a moving coil speaker varies considerably with frequency and the field strength. The rise around 50 to 60 c/s accentuates transformer distortion.

but a speaker varies enormously. Fig. 16 shows the impedance curves of the Celestion E55 speaker. These curves were given to the author by Messrs. Celestion, Ltd., and indicate the variation of speaker impedance with frequency and how this curve changes with the speaker field strength.

The sharp rise of impedance at around 50 to 60 c/s, which is common to all speakers, is serious. It causes the value of R in the formula (3) to increase and the transformer distortion will be accentuated as a result. An example on the lines of those given last week will illustrate the point.

Consider an output transformer for two KT66's in push-pull, having 2,800 turns on a 1½in. stack of No. 4 stampings. This is a more lavish design than that given in Example 2 in Part II, and Table 4 shows that the resultant iron distortion is noticeably less when the anode to anode load is 4,000 ohms. Column 4 applies to this condition and states the total percentage distortion at 50 c/s. If the resistive load be replaced by the E55 speaker (or any other for that matter) the value of R will become much higher than 4,000 at 50 c/s. The AC resistance of the valves is far too high to help very much. R is almost the same as the speaker impedance multiplied by the square of the transformer ratio. Columns 5, 6 and 7 of Table 4 show the total distortion at 50 c/s, when R is equal to 8,000, 12,000 and 16,000 ohms respectively. Although the transformer appears passably good with a resistive load, considerable distortion will be produced in practice when using a speaker in conjunction with high-impedance valves.

It is well known that direct current passing through the primary of a transformer polarises the core and causes a drop in the inductance. One of the advantages of the push-pull arrangement is that the anode currents of the two valves traverse the transformer windings in opposite directions and cancel each other magnetically. But an exact balance of these currents is unlikely unless some special precautions have been taken to ensure it. An examination of the influence of the small out-of-balance currents likely to be met in practice is therefore of interest.

Fig. 8 in Part I showed how the inductance or impedance of a transformer varies with the AC flux density in the core. Fig. 17 repeats this curve together with

TABLE 4

B	Watts Output R=4,000	Zr	Distortion (per cent.)			
			R=4,000	R=8,000	R=12,000	R=16,000
1,000	0.5	28,000	1.85	3.7	5.5	7.4
2,000	2.0	39,000	2.1	4.2	6.3	8.2
3,000	4.6	48,000	2.3	4.6	6.8	9.2
4,000	8.1	52,500	2.5	5.0	7.5	10.0
5,000	12.7	55,000	2.9	5.8	8.9	11.6
6,000	18.0	55,000	3.3	6.6	10.0	13.2

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three additional curves which show how drastically a polarising current reduces the impedance. The values of the DC magnetising force are marked on the curves and they correspond roughly to out-of-balance currents of 2.5, 5 and 10 mA in a transformer such as that analysed in Table 4. Obviously, the effect of even a small out-of-balance current is not negligible. Formula (3) states that the effective distortion will be increased in inverse proportion to Z_F. It follows that some means of securing equality of the

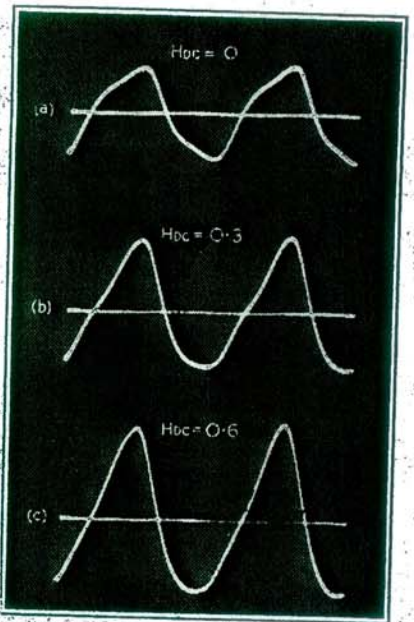

Fig. 18.—Small out-of-balance between the anode currents of push-pull valves is sufficient to reduce the transformer inductance and to add even harmonics to the existing iron distortion.

anode currents should be provided in high fidelity push-pull amplifiers.

Nor is the loss of inductance the only result of polarisation. Fig. 18 gives oscillograms showing the production of even harmonics. At (a) is the current wave form at an AC flux density of 2,920 lines per sq. cm. (no DC component). This oscillogram is the same as the corresponding one in Fig. 3, but the current scale is smaller. Superimposing a DC magnetising force of H=0.3, roughly equivalent to 2.5 mA difference in the anode currents of two push-pull valves, resulted in the wave-form at (b). The current is larger owing to the lowering of the inductance and also the wave form is not symmetrical about the zero line. The latter points to the presence of even harmonics. The third oscillogram (c) shows how both effects are magnified by doubling the DC field strength (H=0.6).

The preceding considerations relating to the effect of DC lead to an interesting line of thought. Imagine two widely different frequencies (DC excluded) being fed into a transformer simultaneously, as must often occur in a normal programme. Periodicities of 50 and 500 c/s would suit the case. How can the higher frequency distinguish between the peaks of the 50 c/s current and a direct current? Fig. 19 makes the similarity between the two conditions easily seen. If the current at the lower frequency behaves in the manner of DC when at its peak values, we should expect the higher frequency to be modulated by the lower frequency.

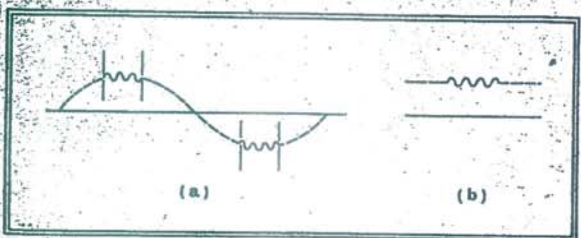

Fig. 19.—Showing the similarity between (a) a high frequency superimposed upon the peak of a low frequency and (b) superimposed upon DC.

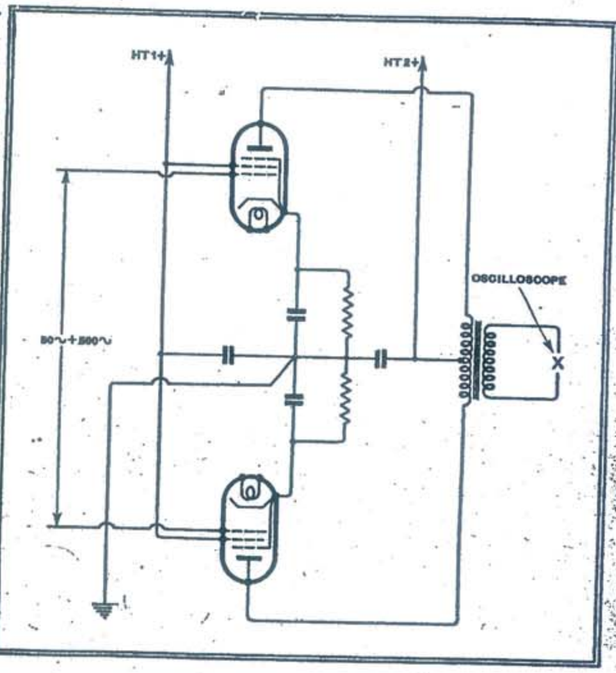

Fig. 20.—The type of circuit employed to obtain the oscillograms reproduced in Fig. 21.

To show that such an effect does indeed take place, a circuit similar to that shown in Fig. 20 was set up. The important points to note about it are: (1) high impedance valves are used, and (2) the transformer is virtually unloaded since the oscillograph has a very high input impedance. The resultant oscillograms, therefore, show the wave form of the open circuit *voltage*, which exaggerates distortion to a maximum as was mentioned in the Appendix to Part I of the series.

Fig. 21 (a) shows the wave form of the 50 c/s output *voltage* when the flux density in the core of the transformer was of the order of 300 lines per sq. cm. At (b) is shown the wave form of the 500 c/s output. The flux density in this case was very small owing to the higher order of the frequency, and, therefore, little iron distortion can be observed. The next oscillogram (c) depicts the state of affairs when the two frequencies were applied together. Note that the 500 c/s wave is not simply added to the wave shown at (a), but it has been modulated as well. The variations of amplitude are

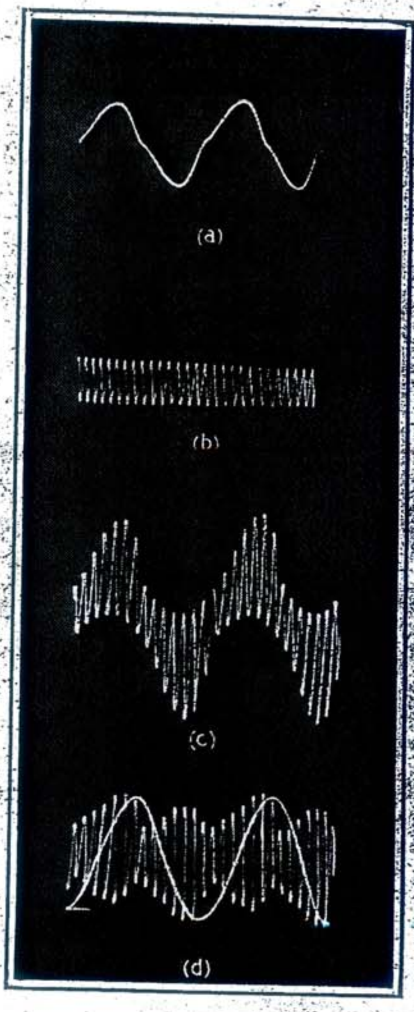

Fig. 21.—The magnetic characteristics of iron are such that high frequencies can be modulated by low frequencies. It is shown in the text that the effect is not very important in practice.

easily detected, but to make it still more obvious, a device was rigged up that allowed the low frequency voltage to be taken out, leaving only the distorted or modulated 500 c/s wave. This is given in

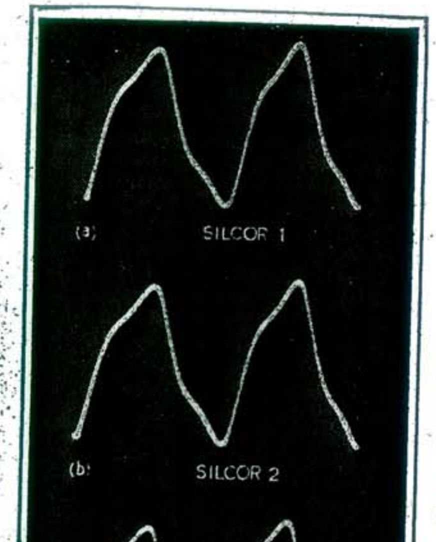

Fig. 22.—The current distortion varies widely with different magnetic materials. The above oscillograms were taken at a flux density of 4,680 lines per sq. cm.

Fig. 21 (d). The sine wave marks the phase relationship of the 50 c/s *current* through the primary, which was responsible for modulating the 500 c/s wave.

In reality the facts illustrated in Fig. 21 (c) and (d) are not quite so simply explained as it might appear from the above. But this is of no immediate consequence. The point is that high frequencies *are* modulated by relatively lower frequencies.

Fortunately, several factors are present that prevent this type of distortion from being prominent in practice. The modulated wave can be looked upon as the original frequency plus a number of others superimposed. Using the radio analogy, the 500 c/s has acquired "side-bands." The transformer can again be accepted as the generator of the unwanted frequencies and a method of calculating the distortion in normal conditions can be deduced. Space does not allow of a full description, but it will suffice to say that the effect is negligible compared with that of the harmonic iron distortion to which this article is mainly devoted.

The laminations or stampings for transformers can be obtained in a number of different magnetic materials. All the results described up to this point have applied to the alloy known as Silcor 2, manufactured by Messrs. Magnetic and Electrical Alloys, Ltd., of Wembley. Other possible materials supplied by the same firm are Silcor 1, Silcor 3, Silcor 4, and a rather different alloy known as Vicor. The magnetic characteristics of each are different and it would be reasonable to anticipate variations in the degree of distortion caused by these alternatives.

To investigate this matter, current oscillograms were taken for each material at a

TABLE 5

Material	Percentage Harmonic Distortion (Current). B = 4,680			
	3rd	5th	7th	Total
Silcor 1 ...	17.3	9.3	10.9	37.5
Silcor 2 ...	20.0	11.1	8.6	39.7
Silcor 3 ...	18.2	9.2	6.3	33.7
Silcor 4 ...	15.6	7.8	3.2	26.6
Vicor ...	14.9	8.0	5.6	28.5

flux density of 4,680 lines per sq. cm. The photographs are reproduced in Fig. 22 and the results of the harmonic analyses are given in Table 5. These oscillograms and the distortion figures obtained from them may be compared with Fig. 3 and the point on the curve of Fig. 5 corresponding to B=4,680. The conditions of test are the same, but the core material is varied. One cannot jump to an immediate conclusion as to the relative merits of these materials merely by consulting Table 5. The basic distortion is not so important as the actual distortion under normal conditions of use and formula (3) told us that this depends upon $x \times \frac{R}{Z_F}$.

R is a constant of the circuit, but x and Z_F depend upon the characteristics of the iron. The values of x are to be found in Table 5 for B=4,680, but Z_F is not dis-

TABLE 6

Material	Z_F	Total Distortion (per cent.)	$\frac{x}{Z_F}$
	B = 4,680		
Silcor 1 ...	460	37.5	.0086
Silcor 2 ...	420	39.7	.0100
Silcor 3 ...	340	33.7	.0105
Silcor 4 ...	265	26.6	.0107
Vicor ...	490	28.5	.0061

closed. A curve similar to that given in Fig. 8 is required for each material. These will be found in Fig. 23. Using the latter curves in conjunction with Table 5 some idea of the merits of the several alloys can be obtained and also some information on how they should be used to the best advantage.

First of all, we will consider the result of substituting one in place of another without altering the windings or core area of the output transformer. Obviously, such a proceeding would change the values of both x and Z_F in formular (3) and the excellence of any particular core will depend upon the ratio $\frac{x}{Z_F}$. In Table 6 the total distortion produced by each grade of iron has been set out, together with the relative values of Z_F extracted from Fig. 23. The final column shows the relative distortion figures $\left(\frac{x}{Z_F}\right)$.

To make the significance of this quite clear, an example will be given. Suppose an output transformer has a core of Silcor 2, such as any of those described earlier in the article. If the iron be removed and, say, Silcor 4 substituted, two major changes in the characteristics of the transformer will be brought about. First, the

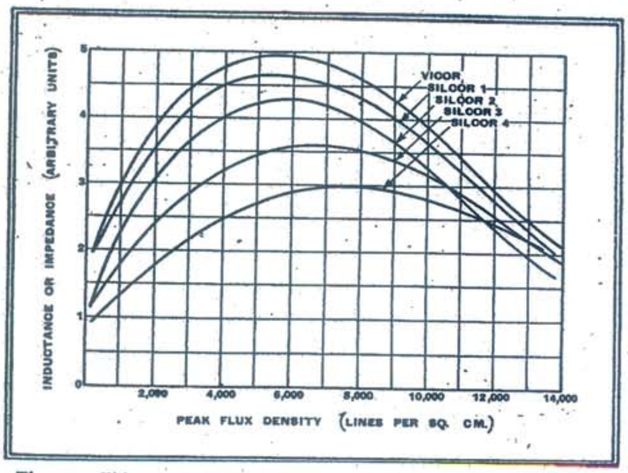

Fig. 23.—This graph illustrates the relative inductances that would be obtained by substituting five different grades of iron in a transformer.

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inductance of the primary will be reduced in the ratio of 420 to 265 (see Table 6) and secondly, the percentage distortion caused by the iron at a flux density of B=4,680 will be increased to 1.07 times its original value. Note carefully that the *iron* distortion will be only slightly increased, but it is possible under certain circumstances that the loss of inductance may considerably increase *valve* distortion owing to the anode load falling below its optimum value.

Looking at each of the samples mentioned in Table 6 in a similar way to that just described, it will be noted that Vicor is outstandingly good. The concluding part of this series will deal with the application of this material to ultra-high fidelity output transformers.

Instead of substituting one type of core for another, the design of the entire transformer might be modified to accommodate the new material. For example, suppose we have a well-designed output transformer with a core of Silcor 4 and, being attracted by the high permeability of Silcor 1, we decide to employ this alloy for the production of an *electrically* similar transformer. The substitution of Silcor 1 for Silcor 4 would increase the inductance from 265 to 460 (see Table 6). Hence one would be justified in reducing the core area in the same proportion in order to end up with the same inductance as the original transformer, which we assumed was adequate. The usual frequency response test would show the new, smaller transformer to be as good as the original large one. But the Partridge Distortion Index would tell a different tale. Since Z_F has been made the same for both transformers, the figure of merit given in Table 6 no longer applies, and the ratio of the basic distortion figures (26.6 per cent. and 37.5 per cent.) must be used. Actually, the position is very much worse than this because by reducing the core area the flux density has been correspondingly increased and, therefore, a much higher distortion figure must be taken for the Silcor 1.

These illustrations show that the substitution of a higher grade of core material results in a small improvement in the iron distortion produced by a transformer. But to employ a high grade for the purpose of reducing size and/or weight results in a substantial increase of distortion. It would seem that a good output transformer *must* be large. Also, a large transformer using low-grade iron will give rise to less harmonic distortion than a small transformer having the same inductance but using high-grade iron.

In fact, the terms "high grade" and "low grade" are not at all applicable as far as speech transformers are concerned. The terms originated with reference to mains transformers, where core losses are so very important and one must guard against wrongly imagining that what is good for a mains transformer is necessarily good for a speech transformer.

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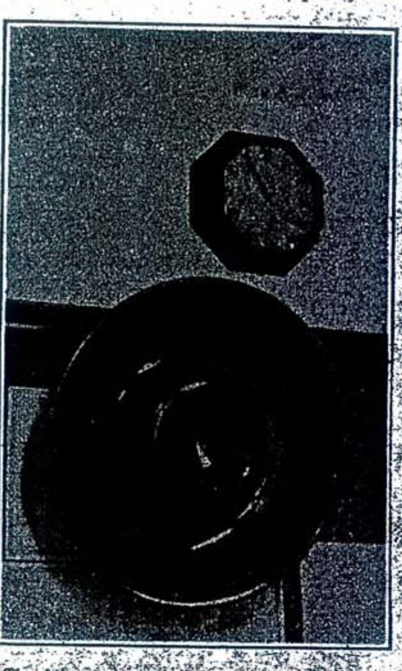

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THURSDAY, JULY 6th.

3, Tennis O.B. from Wimbledon. The Semi-Finals of the Ladies' Singles with a commentary by Thomas Woodrooffe. **3.30,** Gaumont-British News. **3.40,** 257th edition of Picture Page. **4-5,** Tennis O.B. from Wimbledon, continued.

9, Scenes from Henry Sherek's "Dorchester Floor Show." **9.20,** Charles Heslop in "Percy Ponsonby Goes to Wimbledon." **9.30,** British Movietonews. **9.40-10.30,** 258th edition of Picture Page, introducing the Mills Brothers.

FRIDAY, JULY 7th.

2.30-5, Tennis O.B. from Wimbledon. The Semi-Finals of the Ladies' Doubles and the Final of the Men's Singles.

9, Edward Cooper and Patricia Leonard in "Look Here!" a new revue by Nicholas Phipps. **9.30,** Gaumont-British News. **9.40,** "Travelling Light," a description of the contents of a suitcase for a holiday abroad. **9.55,** "Zoo Babies"—Film. **10.5,** Leila Howell, 'cello. **10.15-10.30,** "Sunday in the Country," S. P. B. Mais introduces viewers to his favourite corner of Sussex.

SATURDAY, JULY 8th.

2.30-5, Tennis O.B. from Wimbledon. The Finals of the Ladies' Singles and Doubles, and the Final of the Men's Doubles.

9-10.30, "Gallows Glorious," a special adaption of the play by Ronald Gow. The action takes place in America in 1859.

SUNDAY, JULY 9th.

3, Friends from the Zoo. **3.15,** Cartoon Film. **3.20,** Joan Collier in Songs, with Evel Burns at the piano. **3.30-4,** "The Plough that Broke the Plain"—Film.

8.50, News. **9.5-11.5,** Wendy Hillier as Grace in "The Fame of Grace Darling," a new play by Yvette Pienne.

MONDAY, JULY 10th.

3-4, "Fiat Justitia." Excerpts from Famous Trials of Literature and Drama. Cast includes D. A. Clarke-Smith and Alan Wheatley.

9, Friends from the Zoo. **9.15,** British Movietonews. **9.25,** Musical Bee. **10.5,** Cartoon Film. **10.10-10.20,** "This Motoring," illustrated in verse and cartoon by Reginald Arkell and Harry Rutherford.

TUESDAY, JULY 11th.

3, "Look Here!" (as on Friday at 9 p.m.). **3.35,** British Movietonews. **3.45,** Foundations of Cookery—Marcel Boulestin.

9, Gaumont-British News. **9.10-10.40,** "Inquest," a play by Michael Barringer.

WEDNESDAY, JULY 12th.

3-4.30, "Gallows Glorious" (as on Saturday at 9 p.m.)

9, Foundations of Cookery—Marcel Boulestin. **9.15,** Cartoon Film. **9.20,** "East End"—Talk. **10.5,** Demonstration of Ballroom Dancing by Alex Moore and Pat Kilpatrick. **10.15,** British Movietonews. **10.25-10.35,** Etienne Amyot, pianoforte.