Distortion in Transformer Cores

Part I.—OSCILLOGRAMS AND WHAT THEY REVEAL

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THIS is the first of a series of articles in which the question of amplitude distortion arising in the iron core of a transformer will be dealt with on a quantitative basis. Information on this subject is scarce and the design data given is the outcome of original research by the author.

THERE are two distinct types of distortion in audio-frequency apparatus, (1) frequency distortion and (2) harmonic or amplitude distortion. To achieve ultra-high-quality reproduction it is necessary to study and eliminate both. Obviously, it would be useless to construct an amplifier having a perfect frequency characteristic if it produced, say, 10 per cent. harmonic distortion at normal volume! Yet, strange as it is, this very one-sided treatment seems to be accepted as adequate when referring to output transformers.

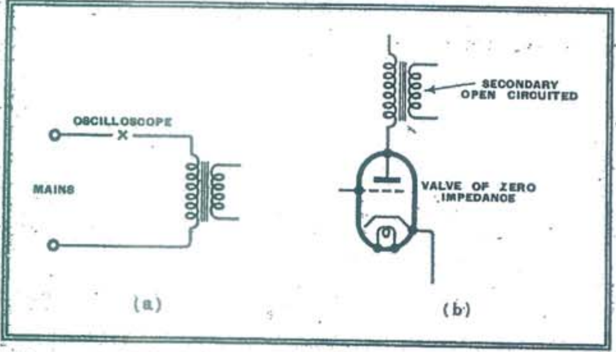

Fig. 1.—At (a) is shown an easy method of observing distortion of the current flowing in the primary of a transformer, while (b) indicates the equivalent valve circuit.

That iron introduces harmonic distortion has been known for a very long time. Text-books and periodicals, not omitting *The Wireless World,* make frequent, if obscure, references to it. "The core must be operated at a low flux density"; "a large core should be employed," etc., are typical observations. But how low must be the flux density and how big the core? Above all, what percentage harmonic distortion normally occurs in an output transformer? A little reflection will bring home the fact that such figures are never called into question. Harmonic distortion has been completely overshadowed by considerations of frequency response.

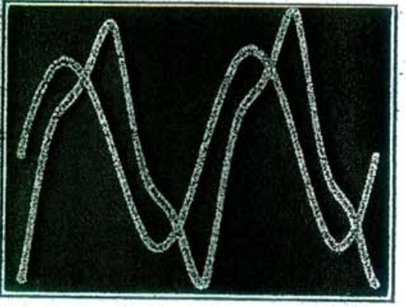

Fig. 2.—A typical oscillogram obtained from the arrangement of Fig. 1 (a).

The simplest way of making the acquaintance of iron distortion is to connect the primary of an output transformer across the 230 v. 50 c/s mains with an oscilloscope in series with it as in Fig. 1 (a). A typical oscillogram is reproduced in Fig. 2.

The sine wave represents the mains voltage applied to the transformer, and the distorted curve represents the current flowing through it. The latter lags behind the voltage, as would be expected with an inductive load, and is badly out of shape. True, the circuit is not the equivalent of that in which output transformers are usually employed. First, the secondary is not loaded, and, secondly, the mains must be regarded as having zero impedance. Fig. 1(b) indicates the corresponding valve circuit. But although the arrangement is not representative of the usual conditions of operation, it will be seen later that it provides a key to all cases. The next step, therefore, is to put our somewhat haphazard experiment upon a more scientific footing.

There is a well-known formula which runs as follows:—

$$B = \frac{\text{Volts} \times 10^8}{4{\cdot}44 \times \text{Frequency} \times \text{Core area} \times \text{Turns}} \quad \cdots (1)$$

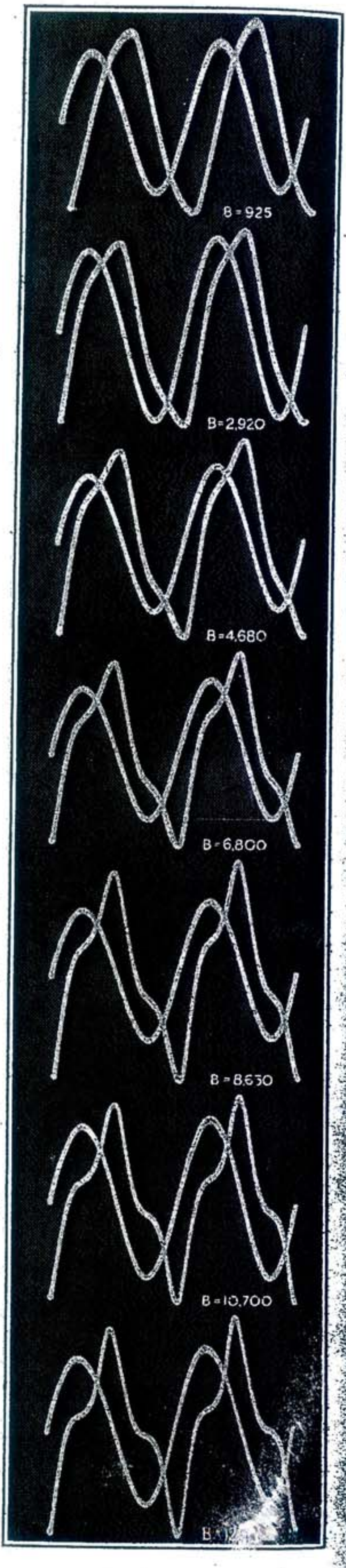

Fig. 3.—A series of oscillograms illustrating how current distortion varies with flux density. "B" is the value of the peak flux density. The core material was Silcor 2.

1T = 10·000 gauss = 64516 lines/sq inch
= 10·000 lines/sq.cm

"B" is the peak value of the flux density reached in the core during a complete cycle. All the constants on the right-hand side of the equation are easily determined. The volts will be 230 or whatever the mains voltage happened to be when the photograph in Fig. 2 was taken, the frequency 50 c/s, the core area (in sq. cms.) can be measured and the turns upon the primary of the transformer can be counted. Thus the peak flux density is readily deduced and our photo is at once elevated from a typical example of distortion to a specific instance of distortion at a known flux density.

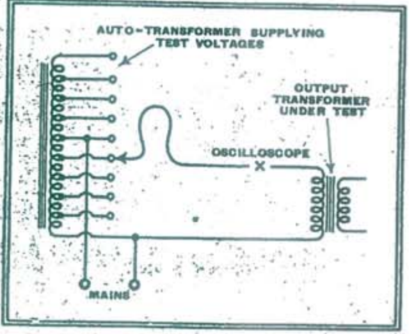

Fig. 4.—A modification of the circuit in Fig 1 (a) which allows observations of distortion at various known flux densities.

An extension of this idea can be added by turning formula (1) round the other way, thus:—

$$\text{Volts} = \frac{4.44 \times B \times \text{Frequency} \times \text{Core area} \times \text{Turns}}{10^8} \quad \ldots (2)$$

By selecting a number of values of "B" for which we should like distortion curves, the required test voltages can be calculated. An auto-transformer will serve to step the mains voltage up or down as necessary and enable us to produce a range of current oscillograms showing how the distortion varies with different flux densities. Fig. 4 outlines the circuit suggested. It is very important to note that a transformer *must* be used for regulating the test voltage. If a series resistance or potentiometer were employed it would act as a series impedance and render the results inconsistent.

Working on these lines, the oscillograms reproduced in Fig. 3 were obtained. The sine curves, in phase with the voltage, were taken for calibration purposes, and can be ignored by the reader; the distorted current curves are all that matter for the moment. The maximum flux density is marked on each photograph. The particular material used for the core of the transformer was Silcor 2, supplied by Messrs. Magnetic and Electrical Alloys, Ltd., of Wembley. This grade of iron is commonly employed for speech transformers, and can be taken as representative of general practice. Obviously, different grades of iron are likely to produce different degrees of distortion. This aspect of the problem will receive full attention later.

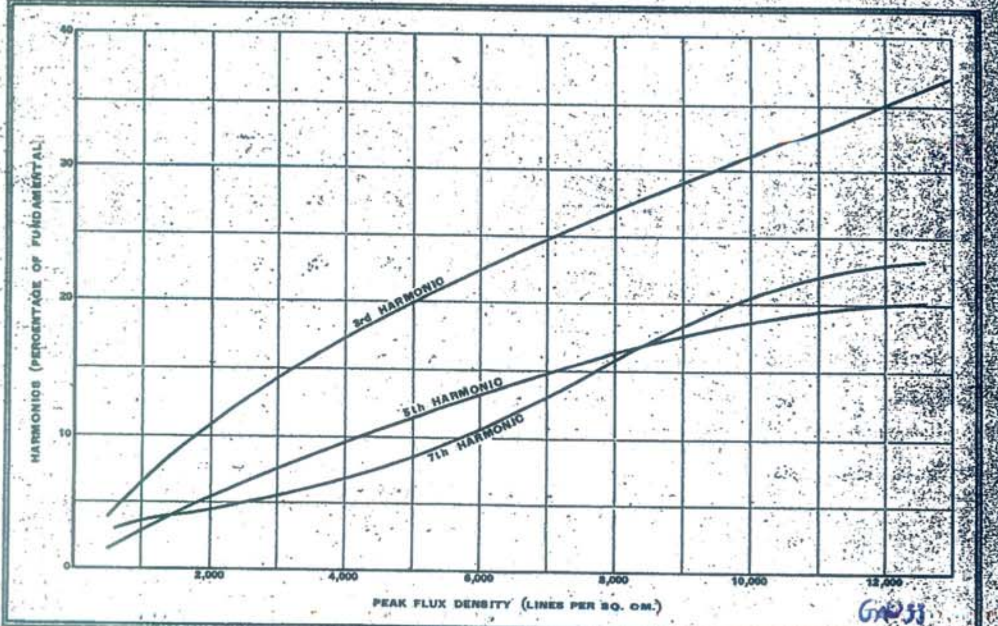

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Fig. 5.—The graph obtained by analysing the oscillograms of Fig. 4. The harmonics are expressed as a percentage of the fundamental. This is a very important series of curves and forms the basis of transformer distortion calculations.

With a modicum of mathematical knowledge and unlimited patience one can analyse the curves of Fig. 3 and produce a graph showing the magnitude of the various harmonics at all flux densities. Fig. 5 gives the result of this labour, and, as will be seen in due course, is a highly important addition to our knowledge of the characteristics of magnetic materials.

The harmonics are expressed as a percentage of the fundamental—i.e., of the true 50 c/s current. Only odd harmonics are present, as would be expected from the symmetrical nature of the oscillograms. Even harmonics result in an unsymmetrical wave shape. The analysis was in all cases extended to the eleventh harmonic, but only the third, fifth, and seventh were found to be of importance.

The meaning of Fig. 5 must be thoroughly understood before proceeding. It shows the harmonics, expressed as a percentage of the fundamental, present in the current flowing through an unloaded transformer when the said transformer is connected across a low-impedance source of such voltage and periodicity as to produce the corresponding flux density. The figures give no direct indication of the distortion the transformer would produce in normal use, but rather represent a characteristic of the core material. We have to find out how these figures may be used as a basis for calculating the performance of the transformer in any specified circuit.

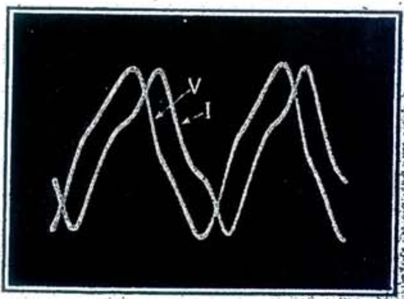

Fig. 6.—Showing how a medium impedance in series with the transformer causes both current and voltage to be distorted.

Increasing the impedance of the AC source—i.e., the mains supply—would bring conditions more nearly into line with those found in practice. Normally, a valve can have an AC impedance of anything from a fraction up to many times that of the transformer primary. The former case occurs when a low-impedance triode is used, and the latter when high-impedance tetrodes or pentodes are employed.

Fig. 6 shows the effect of introducing an impedance of approximately equal value in series with the transformer primary. The flux density was, in this instance, approximately 7,000 lines per sq cm., and the photograph may be compared with the corresponding oscillogram in Fig. 3. Note that both voltage and current have become distorted. This is to be expected, because the transformer draws a distorted current, and therefore the voltage drop across the series impedance must of necessity be distorted. Hence the voltage across the transformer, which is the mains voltage minus the distorted drop across

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the series impedance, must also be distorted.

Evidently an extreme case could be arrived at by making the series impedance very high compared with that of the transformer. Fig. 7 shows what happens under these circumstances. The current becomes a pure sine wave, and the distortion is transferred to the voltage curve. The flux density during this experiment was again maintained at a value of about 7,000 lines per sq. cm. (See Appendix.)

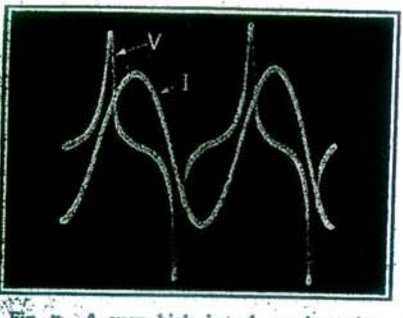

Fig. 7.—A very high impedance in series with the transformer results in distortion of the voltage, but gives a pure sine wave current.

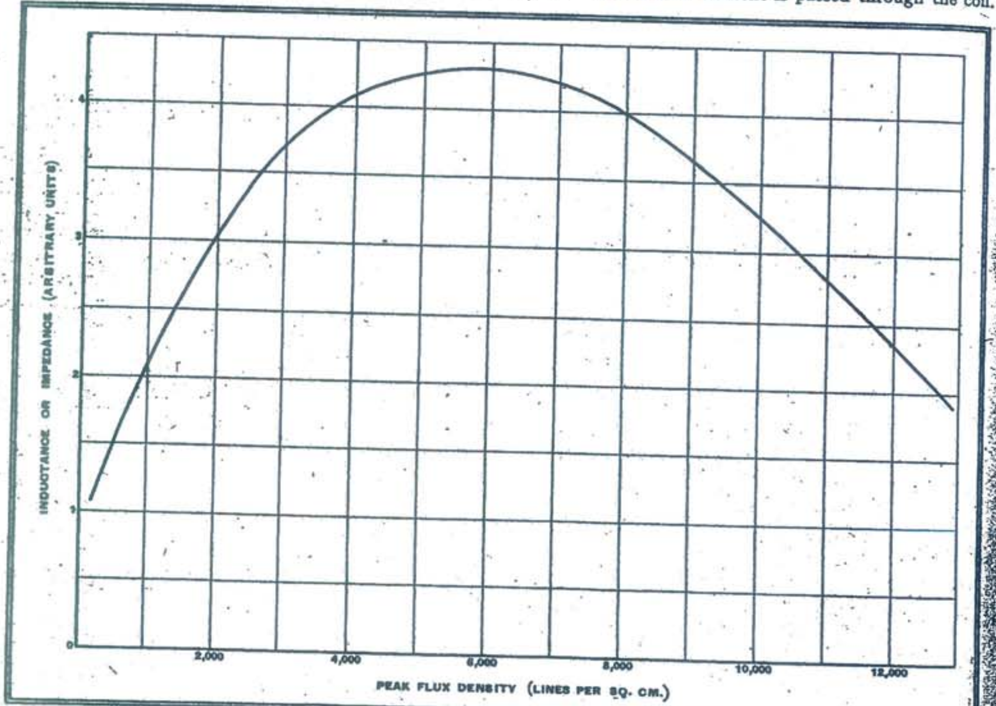

Fig. 8.—Illustrating how the inductance (or impedance) of a transformer, with a closed iron circuit of Silcor 2, varies with flux density. The inductance scale is arbitrary.

To sum up, at one extreme, where the impedance of the AC source is zero, the current is distorted while the voltage remains a pure sine curve. At the other extreme, where the source has a high relative impedance, the reverse is true—i.e., the voltage is distorted and the current a pure sine wave. Clearly, the relative impedance of the transformer compared with that of its associated valve is of considerable importance. A valve impedance is reasonably constant and can be estimated from figures supplied by the manufacturers. But the impedance of a transformer, even at a fixed frequency, is anything but constant, and we must look into this question more closely.

A good many years ago it was the custom of certain manufacturers, and, I believe, of *The Wireless World* as well, to state the inductance of chokes and transformers when *tested at a specified alternating terminal voltage*. This was a very excellent idea, but it has died out, and only the inductance figure is mentioned nowadays. One tends to imagine the inductance of an output transformer as a fixed and constant thing, rather like the resistance of a piece of wire or the capacity of a condenser. Actually, it is entirely dependent upon the test voltage, or, what comes to the same thing, the flux density. A test taken at around 5,000 lines per sq. cm. will give an inductance value perhaps three times as great as that measured at 100 lines per sq. cm.

Impedance Calculations

Definite figures can readily be obtained by replacing the oscillograph shown in the circuit of Fig. 4 by an ammeter. We have already seen how to work out the flux densities corresponding to the several tappings on the auto transformer by using formula (1). The voltage divided by the current will reveal the impedance at each density. The graph of Fig. 8 shows the values obtained plotted against "B."

It is true that impedance is equal to the voltage divided by the current, but in view of the distorted shape of the current wave form we ought to think carefully how it should be measured. The true impedance to 50 c/s will be the voltage divided by the 50 c/s fundamental of the current. The sine curves in Fig. 3 were taken with a known current, so that the analysis of the distorted curves could be converted into actual current values. It was found that the impedances obtained by using the 50 c/s fundamental taken from the oscillograms were practically identical with those given when the distorted current was measured with a rectifier-type meter. This class of instrument gives a reading proportional to the *mean* current.

Returning to Fig. 8, the scale of impedance or inductance is an arbitrary one. The specific values in any particular case will depend upon the size of the core of the transformer and upon the number of turns on the primary winding. But whatever the design may be, the impedance or inductance will vary in the same manner as the flux density is changed, providing the transformer has a closed iron circuit of the same magnetic material—i.e., Silcor 2. By taking a single test at any known flux density, the inductance at any other density can be obtained by reference to Fig. 8.

In Part II it will be shown how the information expressed in the graphs of Fig. 5 and Fig. 8 can be used to calculate the distortion produced by *any* push-pull transformer (providing it has a closed magnetic circuit of Silcor 2) when used in *any* specified circuit.

APPENDIX

An analysis of the wave form illustrated in Fig. 7 gave 58 per cent. third harmonic, 34 per cent. fifth harmonic, and 39 per cent. seventh harmonic. These figures are very much higher than the corresponding percentages present in the distorted current curves (see Fig. 3 and Fig. 5). This is reasonable, because if the distorted current can be represented by:—

$$I = A_1 \sin(\theta + \beta_1) + A_3 \sin(3\theta + \beta_3) + A_5 \sin(5\theta + \beta_5), \text{ etc.,}$$

one would expect distortion of approximately the same order in the distorted flux curve when a sine wave current is passed through the coil. But the induced voltage is proportional to the rate of change of flux—i.e., $\frac{d\phi}{dt}$, and the process of differentiation changes the ratio of the constants to A_1, $3A_3$, $5A_5$, etc.; thus accentuating the harmonics.

No such simple relationship is found in practice. When the flux is distorted the iron losses increase, owing to the presence of third, fifth, and seventh harmonic eddy currents, etc. These losses may be represented as resistive loads across the primary of the transformer tending to reduce the apparent voltage distortion. Hence the accentuation of the higher harmonics in the voltage wave form is not so great as might be expected.