Distortion in Transformer Cores

Part II.—THE "PARTRIDGE DISTORTION INDEX" AND ITS CALCULATIONS

By N. PARTRIDGE, B.Sc. (Eng.), A.M.I.E.E.

IN Part I of this series of articles the author showed that the iron core of any output transformer can give rise to serious harmonic distortion. Part II explains by a number of examples how the magnitude of this distortion may be calculated in practical cases.

IT can be shown both experimentally and theoretically (see appendix) that the harmonic distortion appearing in the voltage across the secondary terminals of an output transformer, having a closed magnetic circuit not polarised by DC, is:—

$$\text{Distortion (per cent.)} = x \times \frac{R}{Z_F} \quad \ldots\ldots \quad (3)$$

where x is the percentage distortion taken from the curves of Fig. 5, R is the parallel impedance of the valve and its external anode load taken together, and Z_F is the impedance of the transformer primary to the fundamental frequency.

TABLE 1

B	Z_F	x from Fig. 5			$x \times \frac{R}{Z_F}$ (R = 2,500)			
		3rd	5th	7th	3rd	5th	7th	Total
2,000	16,000	11.0	5.3	4.5	1.72	0.83	0.70	3.25
4,000	21,800	17.2	9.5	7.0	1.97	1.08	0.80	3.85
6,000	22,900	22.3	13.1	10.6	2.43	1.43	1.16	5.02
8,000	21,200	27.0	16.0	15.6	3.18	1.88	1.84	6.90
10,000	17,300	31.0	18.7	20.3	4.48	2.71	2.94	10.13

The reader is advised not to worry too much about the origin of this formula. Mathematical reasoning is very fascinating, but must not be allowed to interrupt the major line of thought. Our immediate interest is centred upon the behaviour of output transformers, and formula (3) will yield the desired information providing it is used properly. Let us examine the various terms one at a time.

"R" is the combined impedance of the AC resistance of the valve and its effective anode load when connected in parallel. The former is a reasonably constant figure which can be extracted from the data given by the valve manufacturers. It depends upon the characteristics of the valve and the manner in which the valve is used, but is quite independent of the transformer design. The external anode load will be the true load connected across the secondary of the output transformer multiplied by the square of the transformer ratio. The anode load, as calculated in this manner, should normally be the optimum load for the valve.

Z_F and x are both variable, and are dependent upon the frequency and the flux density (B) in the core of the transformer. The way in which Z_F varies with flux density in the case of Silcor 2 has been illustrated in Fig. 8. If the iron losses are overlooked, the simplest method of determining Z_F is to measure the inductance of the transformer primary at any known flux density. The value of inductance at any other density can be deduced from the information contained in Fig. 8, and the impedance, to a sufficiently close approximation for the present purpose, is:—

$$Z_F = 2\pi \times \text{frequency} \times \text{inductance} \quad \ldots\ldots \quad (4)$$

The values of x can be taken directly from Fig. 5, providing the core material is Silcor 2. It can be the percentage content of any one harmonic at the chosen flux density or, alternatively, it may be the total harmonic distortion. It is, of course, absolutely essential that Z_F and x be evaluated at one and the same flux density.

Practical Examples

To examine the degree of distortion that may be found in practice, three different transformer designs will be reviewed. The calculations relating to the first example will be given in full so that the reader can see exactly how formula (3) is used in conjunction with Fig 5 and Fig. 8.

Example 1.—Take an output stage consisting of two DO24 valves in Class "A" push-pull, giving a maximum output of 12 watts. The optimum load given by the makers is 5,000 ohms, anode to anode, and the AC resistance per valve is 2,500 ohms.

A transformer having a primary winding of 2,200 turns upon a 1in. stack of No. 4 stampings of Silcor 2 will have a measured impedance of approximately 21,800 ohms at 50 c/s when the flux density is 4,000 lines per sq. cm. Given this one value of the impedance at a stated flux density it is easy to deduce all the other values by reference to Fig. 8. Table 1 shows the impedance at five different values of B. It should be noted that the primary impedance varies between three and four times that of the optimum load and, therefore, the attenuation at 50 c/s will be very small.

TABLE 2

Frequency c/s	Watts	B	Z_F	x	$x \times \frac{R}{Z_F}$
40	12	12,900	8,180	110.0	33.6
50	12	10,300	16,700	71.0	10.6
70	12	7,350	30,900	54.5	4.4
90	12	5,720	41,300	44.3	2.68
110	12	4,680	49,500	37.8	1.90

Columns 3, 4 and 5 of Table 1 contain the values of x for the third, fifth and seventh harmonics respectively. These are taken directly from Fig. 5. Assuming the ratio of the transformer has been correctly chosen, the anode-to-anode load will be 5,000 ohms. The total valve impedance is also 5,000 ohms (2,500 × 2) and hence R becomes 2,500 ohms. This figure is constant throughout the ensuing

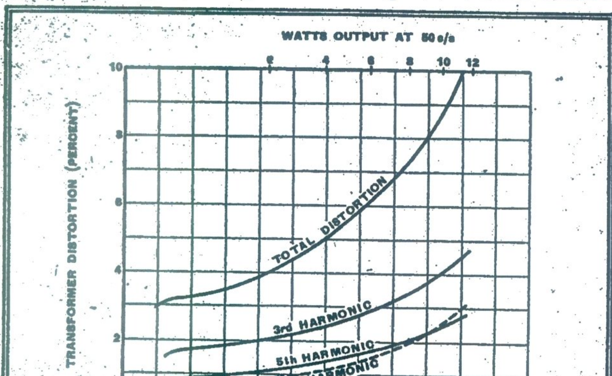


Fig. 9.—The distortion produced at 50 c/s by the transformer described in the text for use with two DO24's in push-pull. Table 1 shows how the figures are calculated.

calculations, but Z_F is different for each flux density.

Returning to Table 1, columns 6, 7 and 8 with the results of multiplying x by $\frac{R}{Z_F}$ while column 9 shows the total distortion, i.e., the sum of columns 6, 7 and 8. These figures have been plotted in Fig. 9 and the curves so produced tell the whole story concerning the distortion caused by the transformer at 50 c/s. By repeating the calculations similar sets of curves could be derived for any other frequency.

In addition to the flux density scale, a scale of watts has been added to Fig. 9. This is derived by using the formula:—

$$\text{Volts} = \sqrt{\text{Anode Load} \times \text{Watts}} \quad .. \quad (5)$$

The voltage across the transformer terminals at any output can thereby be calculated and substituted in equation (1) to discover what value of B corresponds to the output in question.

Another very informative graph is shown in Fig. 10. The derivation of this curve may be traced from Table 2. It

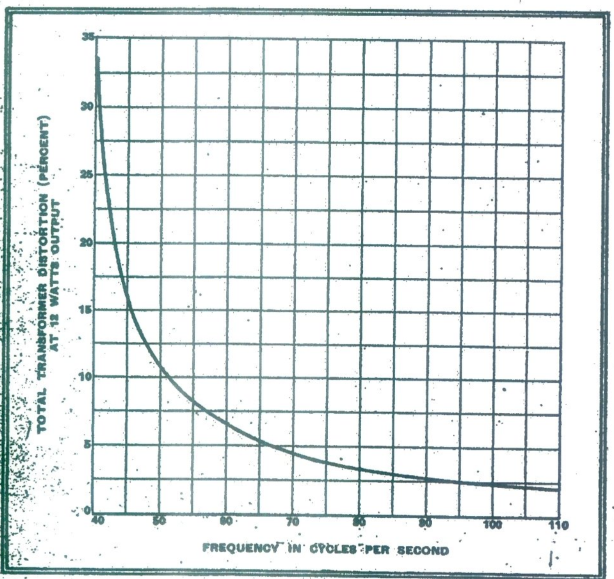


Fig. 10.—Showing how the total distortion at full load varies with frequency. The origin of this curve is indicated in Table 2 and the transformer to which it applies is the same as that analysed in Table 1.

defines the total distortion that would be produced by the above transformer when delivering 12 watts at various frequencies. The total distortion has dropped to 2½ per cent. at 90 c/s. But below about 60 c/s the distortion increases very rapidly. This is due to the combined effect of *higher* flux density and *lower* impedance (Z_F).

The foregoing outline of the calculations relating to the problems of iron distortion have, perhaps, made this section of the article a little heavy. The reader is asked to forgive this, because the subject matter is quite new and, therefore, a full explanation was unavoidable. However, having shown the method, attention can again be turned to the lighter side of discussing the results.

TABLE 3.

B	Z_F	x from Fig. 5			$x \times \frac{R}{Z_F}$ (R = 4,000 approx.)			
		3rd	5th	7th	3rd	5th	7th	Total
2,000	9,630	11.0	5.3	4.5	4.57	2.21	1.87	8.65
4,000	13,000	17.2	9.5	7.0	5.28	2.92	2.15	10.35
6,000	13,600	22.3	13.1	10.6	6.55	3.84	3.11	13.50
8,000	12,700	27.0	16.0	15.6	8.50	5.03	4.92	18.45
10,000	10,300	31.0	18.7	20.3	12.0	7.26	7.90	27.16
12,000	7,400	35.0	20.0	23.0	19.0	10.8	12.4	42.2

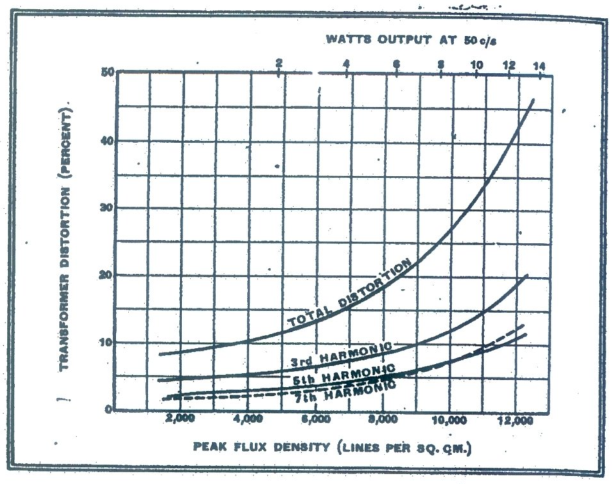


Fig. 11.—High-impedance valves such as tetrodes or pentodes accentuate the transformer distortion. These curves apply to a transformer working in conjunction with two KT66's.

The transformer selected for Example 1 is obviously useless as far as high-fidelity reproduction goes. Somewhere around 10 per cent. distortion at 50 c/s is far more than can be tolerated. But the reader should observe with special care that the transformer would be classed as very good if judged by the normally accepted standards. Taking the usual "selling points" one at a time we find:—

(1) *Frequency Response.* This is excellent. The primary impedance is three to four times the load impedance at 50 c/s (*The Wireless World* has often recommended a ratio of two as being adequate), hence the bass is well looked after. The high-frequency response depends only upon the method of winding the bobbin and can be taken as level up to 20,000 c/s for the sake of argument.

(2) *Ratio.*—Our calculations have assumed that the ratio was exact.

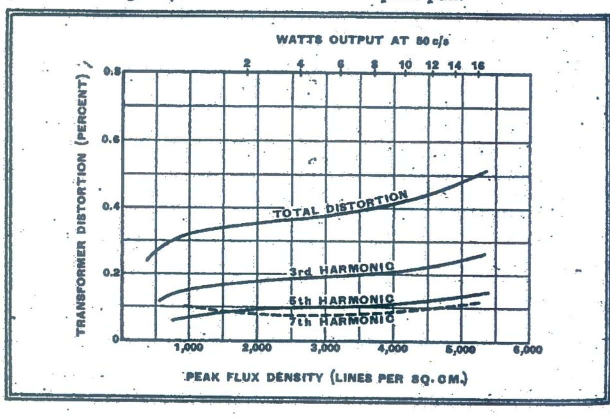
(3) *Resistance of Windings.*—The primary resistance would be in the region of 80 ohms total, which is commendably low for an optimum load of 5,000 ohms.

Defining Performance

The author has frequently made derogatory remarks concerning the present craze for lauding frequency response as a proof of excellence. And here we have a typical example of its very limited indications. The transformer examined above passes the much vaunted "straight line" test with flying colours, in spite of being in fact a very third-rate article.

Obviously, additional tests are indispensable. A statement of harmonic distortion is imperative for the purpose of comparing the merits of various output transformers. The author suggests that a very simple scheme would be to state *the total percentage distortion produced at 50 c/s when the transformer is delivering its*

Fig. 12.—Illustrating how small the harmonic distortion due to the output transformer can be made by careful design. These curves apply to the 50 c/s performance of a transformer working with two DA30 valves in push-pull.



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full rated output into a resistive load, of value equal to the nominal secondary load. The corresponding figure for the above transformer would be 10.6 per cent. It must be remembered that such a distortion index is arbitrarily chosen and, in order to emphasise this and to avoid confusion with other possibilities, it will be referred to as the *"Partridge Distortion Index."*

Example 2.—As a second example we will try two KT66 valves in push-pull, operating with an anode-to-anode load of 4,000 ohms. The AC resistance is very high (about 25,000 ohms each) and the output 17 watts.

Again keeping the No. 4 stampings and winding 1,700 turns upon a 1in. stack, the impedance will be as indicated in Table 3. The distortion curves are reproduced in Fig. 11, which corresponds to Fig. 9 of the previous example, and it can be seen that the Partridge Distortion Index is too high to be estimated. Note that once more the frequency response curve would proclaim the transformer as good.

It will be appreciated from this example that high impedance tetrodes and pentodes accentuate transformer distortion. With triodes the value of R is usually considerably less than that of the optimum load because of the effect of the AC resistance of the valve. In the present case R is approximately equal to the optimum load since the valve impedance is too large to have much effect.

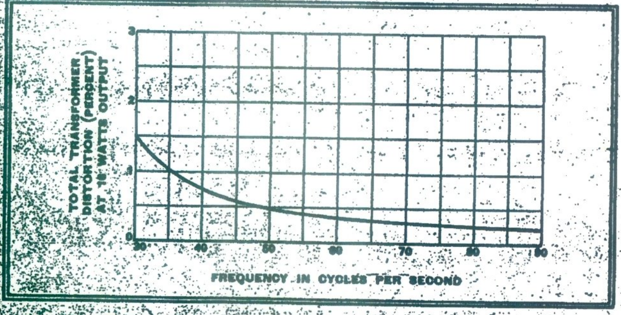

Fig. 13.—These curves relate to the same transformer as Fig. 12 and show how the distortion at full load varies with frequency.

Example 3.—As a final illustration which can be taken as representative of good design, a transformer for use with two DA30's will be described. These valves require an anode-to-anode load of 9,000 ohms in Class "A," and give a speech output of 17 watts.

The transformer uses a 1¼in. stack of No. 4 stampings and is wound with 4,400 turns on the primary. Fig. 12 shows the distortion at 50 c/s. In this case the Partridge Distortion Index is 0.5 per cent. which is very satisfactory. In Part IV of this series it will be shown how even better results are possible by using a different magnetic material and a modified design technique. Fig. 13 shows how the distortion at full output varies with frequency and corresponds to Fig. 10 relating to Example 1.

When reviewing the latter curve (Fig. 13) it must be borne in mind that the full output at 30 c/s can never be expected in normal use. If the full output is devoted to one frequency, nothing can be superimposed upon it without overloading the output stage. But music consists of many frequencies, all reproduced at one and the same time. Hence the amplitude of the bass notes must be small compared with the maximum amplitude permissible. In the opinion of the writer the distortion on full load at 50 c/s can be taken as the maximum distortion likely to be encountered in practice.

As a parting reflection, how can the obvious superiority of the transformer described in Example 3 be detected by the tests usually applied to this type of component? Clearly it would be judged as simply another good transformer. What further proof is necessary to demonstrate

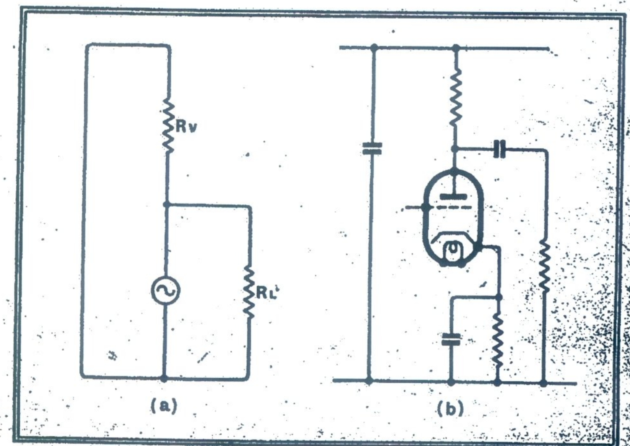

Fig. 15.—At (a) is shown Fig. 14 (c) inverted. It is analogous to the usual valve circuit illustrated at (b).

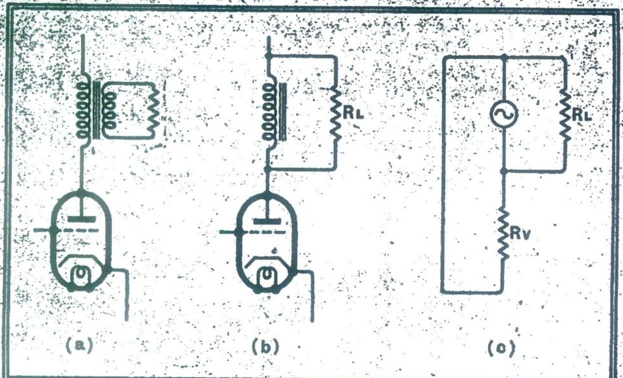

Fig. 14.—Circuit (a) is the usual output transformer diagram which can be represented as at (b) by suitably choosing the value of R_L. (c) is the equivalent of (b) if the transformer is considered as a generator.

APPENDIX

To prove that the percentage distortion produced by an output transformer is equal to $x \times \frac{R}{Z_F}$, consider the output transformer as a generator of harmonics. Fig. 14 (*a*) can be reduced to Fig. 14 (*b*), which is equivalent to Fig. 14 (*c*). Next, turn Fig. 14 (*c*) upside down. This has been done in Fig. 15 (*a*) and the similarity between this and the usual valve circuit of Fig. 15 (*b*) becomes at once apparent.

Falling back upon the well-known valve calculations, the harmonic voltage appearing across the load will be :—

$$V_H \times \frac{\text{External Impedance}}{\text{Generator Impedance} + \text{External Impedance}} \quad (6)$$

where V_H is the open circuit harmonic voltage.

Let Z_F = primary impedance to fundamental frequency.

I_F = value of current at the fundamental frequency.

Z_H = primary impedance to any specified harmonic.

V_H = internally generated voltage of specified harmonic.

x = harmonic current produced by V_H expressed as a percentage of the fundamental current (I_F) when the external impedance is zero. Values of x were given in Fig. 5.

V_H = short circuit current × primary impedance.

$$= \frac{x}{100} I_F \times Z_H$$

Normal External Load (see Fig. 15 (*a*).) $= \frac{1}{\frac{1}{R_L} + \frac{1}{R_V}} = R$ (say)

Total impedance of the circuit (see Fig. 15 (*a*).) $= R + Z_H$ $= Z_H$ approx.

This approximation is justified in normal cases because Z_F is at least equal to R in any reasonably well-designed transformer, and Z_H will be several times Z_F since impedance increases almost in proportion to frequency. The addition of R and Z_H must be vectorially performed and is numerically approximately equal to $\sqrt{R^2 + Z_H^2}$ which is nearly equal to Z_H because Z_H^2 is large compared with R^2. Therefore :—

Harmonic voltage across load by substitution in equation (6)

$$= \frac{x}{100} I_F Z_H \times \frac{R}{Z_H} = \frac{x I_F R}{100}$$

Fundamental voltage across load $= I_F Z_F$.

Therefore the harmonic voltage appearing across the load expressed as a percentage of the fundamental voltage becomes :—

$$\frac{x I_F R/100}{I_F Z_F} \times 100 = x \frac{R}{Z_F}$$

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the immediate necessity for a statement of the Partridge Distortion Index or some other figure that will serve as a reliable guide? It is the only way the genuine article can be distinguished. A "straight line" response is not a passport to the land of high fidelity. The elimination of harmonic distortion serves a more useful purpose than the retention of frequency bands beyond the range employed for radio or gramophone.

Letters to the Editor

The Editor does not necessarily endorse the opinions of his correspondents

A.R.P. and the Amateur

TO the initiated, the value of portable or fixed wireless sets for maintaining communication under difficult circumstances during emergencies is so well known and appreciated that it seems unnecessary for its advantages to be stressed, but despite that fact the Home Office still sets its face against the employment of radio in A.R.P. communications. It is quite obvious that the first bomb may deprive a town completely of its line communications and render practically the whole of its A.R.P. service useless. The extra strain put upon the much-vaunted loop lines, which in their turn may also be put out of action or destroyed, would not solve the problem, and the use of runners or cyclists through shrapnel-infested streets, probably made impassable by bomb craters to wheeled traffic, may possibly only add to the list of killed or wounded and still fail to bring help to the stricken area. Small portable transmitter-receivers could and would maintain reliable communication under all conditions except that of a direct hit without endangering one extra life. The necessary training could be given by members of the transmitting fraternity, say under the auspices of the Radio Society of Great Britain, who could organise those members willing to help, either as operators or to train personnel.

Thus the Home Office would have the use of a body of men who could, if unlikely to be called up for other services, maintain control or controlled stations at their homes, or use portables as required. Others who have become members of the fighting Services, or who would be in line for such Services in the event of war, could help in the training of additional A.R.P. helpers.

I was interested to see that the police have taken such a course, and are installing wireless apparatus in every police station in the metropolitan area. What about forming a section of the "Specials" to include amateurs who would be prepared to operate the sets?

The Home Office has a fund of useful material at its very door, but unless they wake up before the advent of war it will be too late to take advantage of that fact. Many members of the amateur fraternity, though adverse to war and all its causes, would not hesitate to assist in the protection of their homes; and many too old for more active service could render valuable assistance as wireless operators. If scattered, it would be difficult to re-form the ranks, and their usefulness would probably be spent in less valuable work. Let the Home Office awake to its responsibility.

W. E. F. CORSHAM (G2UV).
Wembley, Middlesex.

Qualifications of Service Personnel

MAY I ask Mr. G. L. Morrow to qualify his statement "that a high standard of technical knowledge in the Services is unnecessary and even undesirable"?

Radio development is very active in the Services just now, and, let us hope, will continue to be so.

How, then, are operators, suddenly confronted with new sets embodying new designs and principles, going to be able to operate, maintain and modify them if they lack sufficient fundamental knowledge to enable them to keep abreast of such development?

Also, Mr. Morrow lays stress on the use of analogies, whereas anyone who has tried to learn radio theory by such evasive methods knows only too well their ability to "lead one up the garden path."

And, sir, if we are to believe Mr. Morrow, the radio branches of the Services are peopled by automatons whose brains respond to morse symbols, but shy like a startled faun when confronted with anything more formidable than $I=\frac{E}{R}$. Are we to assume, therefore, that the pages of *The Wireless World* are looked upon as a foreign journal by such people?

Men leaving the Services and seeking positions in the radio profession will surely object to any such inference, whilst serving personnel will just as surely deplore the obvious insinuation that their ability to assimilate knowledge is strictly limited.

In conclusion, may I congratulate Mr. Morrow on having found such a comfortable armchair from which to air his views?

Cranwell, Lincs. J. CLARKE, Cpl.

News from Japan

THE following may be of interest to those of your readers owning SW receivers and able to take down morse:—

"Domei English broadcast, European zone, 8 G.M.T. Starting Wednesday, June 21st, Station Tokio Oyama; call sign JUQ; frequency 18,080 kc/s."

This announcement was given at the conclusion of the English broadcast on June 20th from JUP on 23 metres at approximately 13.00 G.M.T. Speed about 20 w.p.m.

Sunderland. A. HARGREAVES.

Pirate Transmitters

A YEAR or more ago you were kind enough to publish a letter from me notifying readers of *The Wireless World* that my call sign G2MQ was being wrongfully used by some unauthorised transmitter. The publication of the letter (in which I indicated that I was taking legal action against the person concerned, if found) brought about an immediate cessation of the activities of the pirate in question, but they have apparently started again, for this morning I have received a QSL card from two different parts of the world (I do not wish to give the pirate the satisfaction of knowing where they are from) identifying a particular transmission which removes all doubt of the call sign having been misread. Particulars are appended to this letter, but not for publication.

As one of the pioneers of amateur radio in this country I maintained my transmitting licence until last year, although I have had no transmitter in operation for several years. As a result of this repeated infringement and the inability of the Post Office, in spite of frequent notifications from me, to track down the infringer, I gave up the licence in question, and shall therefore be glad if readers of *The Wireless World* will delete my name from their list of call signs. At the same time I would like to repeat that, if the infringer is identified, I shall consider it my duty to other experimenters who abide by the regulations, to give all the assistance in my power to the authorities in any prosecution which may be decided upon. I will also take independent action if possible.

PERCY W. HARRIS.
Wimbledon, London, S.W.19.

Frequency Modulation

FROM the point of view of a purist in nomenclature, "Heptode" (*The Wireless World*, June 15th) is perhaps right in saying that frequency modulation is a different thing from phase modulation; but in actual practice the name frequency modulation is given to a process that is nothing more nor less than simple phase modulation. The definition of frequency modulation, quoted by "Heptode" from J. E. Young's "Electric Communications and Electronics," has nothing to do with frequency modulation as dealt with by radio engineers or radio physicists.

He says that a single frequency current can be expressed as

$$i=A \sin(2\pi ft+\theta),$$

where A is the amplitude, f is the frequency and θ the relative phase. Then he says that if f is slowly varied the wave is said to be frequency modulated. The discussion below shows that this kind of modulation does not occur in practice.

Suppose f is varied slowly by replacing the constant f by a variable $f(1+k \sin 2\pi Ft)$. F is the frequency of modulation of f and is assumed small compared with f; k can be regarded as the modulation depth of f and may be assumed small compared with unity. The current now is

$$i=A \sin(2\pi ft+\theta+2\pi kft \sin 2\pi Ft).$$

By sketching a graph of the argument, t,

$$2\pi ft+\theta+2\pi kft \sin 2\pi Ft,$$

it is not hard to see that this new value of i is a function oscillating between positive and negative values, the number of such oscillations per second increasing indefinitely with time. The reason for this behaviour is that since f in the original expression for i was multiplied by the time t, the variation is also multiplied by t and becomes greater and greater as time goes on. In other words, the radio engineer looking at this current, either on an oscillograph or with tuned circuits, would say that its frequency was increasing with time without limit. It is hardly necessary to add that the radio engineer never does look at such a current.

Young's definition of frequency modulation is thus quite academic. It is easy to show that phase modulation, as defined by him and by others, is what radio engineers, and their tuned circuits, commonly regard as frequency modulation.

PRO BONO RADIO.
Farnborough, Hants.