Measurement of Non-Linearity Distortion

By
M. G. SCROGGIE, B.Sc., M.I.E.E.

Need for a Method Corresponding with Aural Judgment

DESPITE television, interest in sound-reproducing equipment was never greater. For evidence one has only to look at the advertisement pages of this journal. It can hardly be denied however that present practice in specifying the non-linearity of such equipment is unsatisfactory. Out of a considerable number of specifications that were examined, one of them stated the percentage total harmonic distortion at a mentioned power output at two frequencies (40 c/s and 2 kc/s), one gave the same information at a single frequency (1 kc/s), one gave a curve of "total distortion" against watts output (frequency not stated), six gave the "distortion" or "harmonic distortion" or "total harmonic distortion" at a stated output but no stated frequency, two were "undistorted" up to a stated output, and the remainder were even vaguer.

What is the information we really want? Presumably something that will tell us how much unpleasantness we may expect at the maximum output, or alternatively how much output is available up to the point at which unpleasantness does not exceed a specified amount.

The basic principles of this matter have been reviewed so recently by "Cathode Ray"[1] that the preliminaries can be abbreviated. As he says, unpleasantness is not measurable as such, so the only hope of obtaining quantitative information is to find some physical characteristic to which audible distortion is as nearly as possible proportional and measure that. There are of course various types of distortion. Of these, it can be assumed nowadays that frequency distortion can readily be brought under control. The other main type, to which the present discussion will be confined, is non-linearity. Unlike frequency distortion, the results of non-linearity in one unit of the audio chain cannot be compensated by opposite non-linearity in another.

Simple Methods

The problem is to observe and specify non-linearity so as to show how far it causes the reproduction to fall short of perfection. One common method is to apply a sinusoidal signal to the unit under test and to display the output waveform on an oscilloscope, using a linear time base. The fact that this is so often done can only be accounted for, surely, by the comparative ease of the procedure. The degree of distortion can be judged only by comparing what is seen with an invisible mental picture of a perfect sine wave, so the minimum that can be detected depends largely on the experience and skill of the observer and at best is not very small. A considerable improvement is to use a double-beam oscilloscope and compare the output waveform directly with the input, but even then the method is not sensitive enough for nearly linear units. It has its uses, but can hardly be classed as a method of measurement.

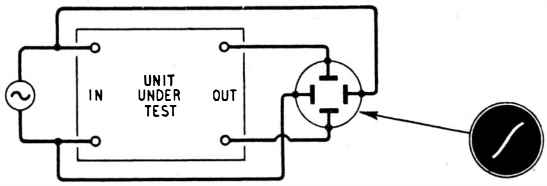

Fig. 1. In this c.r.o. method of measurement the cause rather than the effect of the distortion is seen—the non-linearity of the transfer characteristic.

Another oscilloscope method is to display the transfer characteristic—the graph of instantaneous output against instantaneous input—by connecting as in Fig. 1. The ideal pattern is a perfectly straight diagonal line. One can much more easily judge departure from a straight line than from a sinusoid, and also more easily distinguish the nature of the distortion. But even so, the method is effective only for what would nowadays be considered comparatively gross distortion.

Need for a Single Figure

Obviously distortion shows up much more clearly if the comparatively large undistorted component of the output is removed. Both simple[2] and elaborate[3] arrangements have been described for filtering out the fundamental output and displaying the remainder —the distortion products—on the oscilloscope screen. This can be a most effective way of investigating distortion. But although distortion oscillograms are extremely informative to any one who can interpret them, for general purposes they have serious disadvantages. They cannot be communicated verbally. They are troublesome to reproduce accurately without photography. And they cannot readily be compared quantitatively with one another, nor enable the signal level to be set to a specific standard of distortion. So the need remains for some method yielding results that can be expressed numerically, preferably as a single figure.

Since the effect of non-linearity is to create signal components or products at frequencies not present in the original, the obvious solution is to compare the amplitudes of these products with that of either the whole output or the undistorted part of it. Stated in this way, the problem looks quite simple, but the more one examines it the more complicated and difficult it turns out to be. That is, if we have not forgotten that our quest is a measure that corresponds reasonably well with aural judgment.

The first complication arises from the division of distortion products into two classes—harmonics and intermodulation products. This division is a useful one for distinguishing products whose frequencies are multiples of the originals from those with sum and difference frequencies. But it is not such a basic distinction as is sometimes supposed.

The other outstanding question is whether and how the distortion products, if there are more than one, can be combined into a single distortion figure. There is no difficulty in combining as many as one likes, but again one must not forget the aim. Does the combined figure reliably correspond with aural judgment?

Whatever their reasons may be, advertisers of high-fidelity amplifiers seem at present to be in complete agreement on these two matters. If distortion figures are mentioned at all they shall be (1) harmonics and (2) a single figure, viz., total harmonics expressed as a percentage of the whole output[5]. This total is the r.m.s. voltage of all the harmonics together, and the distortion figure is therefore

$$100\sqrt{\frac{V_2^2+V_3^2+V_4^2+\ .\ .\ .}{V_1^2+V_2^2+V_3^2+V_4^2+\ .\ .\ .}}$$

where V_1 is the voltage of the fundamental, V_2 the voltage of the second harmonic, and so on. Although this whole expression may look rather complicated*, it is perhaps the easiest distortion figure to measure, which is presumably the reason for its common use. The apparatus (Fig. 2) consists of an oscillator with substantially less harmonic content than any equipment to be tested, a bridge or other device for balancing out the fundamental, and an amplifier and meter (theoretically r.m.s., but often not so in practice) for reading the distortion and comparing it with the total output. Such combinations are available commercially and can be used by unskilled persons.

When the distortion to be measured is of the 0.1% order, the requirement regarding purity of oscillator output is stringent, and filtration is likely to be needed; this in turn makes one anxious not to have to vary the frequency much. It is, of course, necessary to know the signal level or output power at which the distortion is read, and at a given level the distortion usually depends largely on the frequency. So unless the frequency also is stated, the significance of the reading is considerably reduced. If unmentioned, one would probably be safe in assuming it to be some middle frequency, such as 400 c/s or 1,000 c/s, and can only conjecture what it would be at 40 c/s!

"Weighted" Components

There is general agreement that the unpleasantness of a given percentage distortion, as measured in this way, depends to a very large extent on how that percentage is made up. If 1% total distortion consisted of 1% second harmonic and nothing else, it would sound very much better than if the first 13 harmonics were all present to the extent of 0.29% each (making the same total r.m.s. value). Therefore in the absence of further information the "total harmonic distortion" is a very unreliable indicator of unpleasantness.

In order to bring the total harmonic reading more into line with aural impressions it was proposed as long ago as 1936[6] that the higher harmonics should be "weighted" in direct proportion to the number of each harmonic, by multiplying the *n*th harmonic voltage by $n/2$. The percentage, weighted in this way, can be written

$$100\sqrt{\frac{V_2^2+(\frac{3}{2}V_3)^2+(2V_4)^2+\ .\ .\ .}{V_1^2+V_2^2+V_3^2+V_4^2+\ .\ .}}$$

In 1950 D.E.L. Shorter[7] produced evidence to show that this linear weighting is not drastic enough and that aural assessment is fitted more closely by a square law:

$$100\sqrt{\frac{V_2^2+(\frac{9}{4}V_3)^2+(4V_4)^2+\ .\ .\ .}{V_1^2+V_2^2+V_3^2+V_4^2+\ .\ .\ .}}$$

He admitted a practical difficulty, that high harmonics present in quantities insufficient to be accurately measured may nevertheless, when weighted thus, contribute significantly to the total.

On a basis of musical harmony theory, one would not expect the unpleasantness of harmonics to conform to any simple law. For instance, the 15th is *less* discordant than the 13th. But Shorter suggests that the fact that his weighting gives a figure related to the sharpness of curvature of the waveform may be significant. Some further research on this would be helpful.

Intermodulation Distortion

It is not difficult to guess why weighted systems have failed to achieve popularity. In the first place, though it be granted that they are a closer approach to our ideal, they seem somewhat arbitrary and thereby lacking in authority. Perhaps more decisively from a commercial viewpoint, they give figures higher than the unweighted total, and so there is what in official jargon would be called a strong disincentive to use them. It is rather surprising that no one has thought of advertising on a system in which the *lower* harmonics would be *divided* by an appropriate factor! Lastly, the apparatus is more complicated, though for simple proportional weighting not unduly so—details of a suitable instrument were given long ago[6].

Although one rarely, if ever, sees a weighted distortion figure, the more highly technical specifications do occasionally reveal the separate percentages of the first few harmonics. Such figures can be derived from the output waveform or the transfer characteristics, but only with a good deal of effort and when the distortion is fairly large. For general purposes it is best to measure them individually with a wave analyser, of which more anon.

So much for harmonics; how about intermodulation? It is sometimes regarded as quite a different kind of distortion. There is certainly general agreement that the unpleasantness of non-linear sound reproduction is due more to intermodulation products than to harmonics.[1, 8, 9]. Therefore, some say, intermodulation is inherently a more reliable index to distortion than harmonics. But this does not necessarily follow, and if intermodulation is chosen it should be for some better reason.[1] For basically they are the same, and theoretically, given complete information about harmonic production, it is possible to calculate the intermodulation products, and vice versa.[8, 10]. Or given the

* But unless the distortion is more than about 10%, the denominator $\sqrt{V_1^2+V_2^2+V_3^2+V_4^2+\ .\ .\ .}$ can be replaced, with negligible error, by V_1.

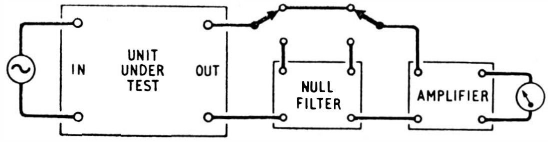

Fig. 2. Block diagram of the usual arrangement for measuring total harmonic distortion.

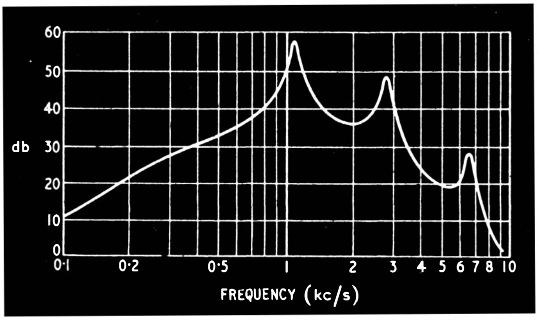

Fig. 3. Example of a frequency characteristic in which wide divergences between different methods of estimating distortion are to be expected.

non-linearity and input signal amplitudes, the amplitudes of both harmonics and intermodulation products follow, so that the ratio of one to the other is known.[11, 12, 13] From this it seems reasonable to conclude that either should do almost equally well as a measure of distortion. On the other hand, however, many workers state that intermodulation data line up well with listening tests whereas harmonics do not.[8, 14-20]

From these many references let us take two examples. The first is by H. E. Roys.[15] He compared the total harmonics with total intermodulation resulting from the playing of disk records of test signals (400 c/s alone and 400 c/s with 4,000 c/s), using styli of specified point radius. He repeated the tests with "masters" (electroplated "negatives" of original engraved disks) that had been excessively polished, resulting in shallow flat-bottomed grooves in the pressings. These tests showed a great increase in audible distortion and in total intermodulation, whereas total harmonic readings were hardly affected. Roys concluded that whereas the intermodulation method of test corresponded with audible distortion, the harmonic test did not. And since he confined this conclusion to disk recording and reproducing, there seems to be no reason to question it. But it has been quoted by others[17] as evidence that intermodulation can vary quite independently of harmonics in the circumstances generally assumed, viz., two or more signals being handled simultaneously by a non-linear unit, such as an amplifier or gramophone pick-up. The nature of Roys' experiment, however, was entirely different, involving intermediate mechanical processes not subject to the usual assumptions about non-linearity. On the information available, it seems likely that the polishing affected the 4,000 c/s ripple most at the peaks of the 400 c/s waves, which would result in 400 c/s modulation of the 4,000 c/s in the reproduction without necessarily causing much distortion of the 400 c/s reproduction. Roys' argument for preferring intermodulation tests, while justifiable for the particular chain of processes with which he was concerned, is

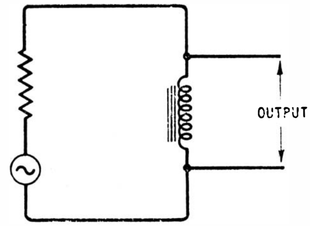

Fig. 4. A simple frequency-discriminating system, representing a typical output stage, in which the ratio of intermodulation to harmonic distortion is very different from that calculated for systems with level frequency characteristics.

quite invalid for non-linearity as generally understood.

The second example[18] is one in which a particular form of intermodulation test on a deaf aid was found to correspond much better with aural tests than did the measurement of harmonic distortion. Examination of the distortion/frequency graphs obtained, however, shows that the frequency characteristic of the aid contained sharp peaks and deep hollows, and that these were responsible for the lack of proportionality between harmonic and intermodulation products. The strong indication of distortion by the preferred method of intermodulation measurement was due mainly to the frequency of the product measured, and a different kind of intermodulation method gave altogether different results. It is well that those of us whose distortion measurements are confined mainly to equipment with nearly flat frequency characteristics should be reminded that the simplifying assumptions that can be made for such equipment do not hold when the frequency characteristic is mountainous. Take for example the frequency characteristic shown in Fig. 3 and compare the distortion at 2 kc/s when measured as (a) the second harmonic, 4 kc/s, and (b) the difference frequency, 1.1 kc/s, between input signals at 2 kc/s and 3.1 kc/s. The amplification at 4 kc/s is more than 30 db down on that at 1.1 kc/s, so it is not surprising if method (b) gives a much higher reading under these conditions than method (a).

The moral is to refrain from applying to one set of conditions a conclusion established for quite a different set of conditions.

Influence of Frequency Response

The conditions for which a definite intermodulation/harmonic ratio (usually between 3 and 4) has been calculated[11,13] are ideally simple: frequency characteristic perfectly level over a band embracing all the frequencies involved, and transfer characteristic conforming to a simple power series. Even so, the ratio depends on the number and coefficients of the terms in the series, and on the relative amplitudes of the test signals. The influence of frequency response

TABLE I

Order of Distortion	Harmonic		Intermodulation	
	Frequency	Percentage	Frequency	Percentage
3rd	180	8.0	520	3.3
5th	300	2.3	640	0.67
7th	420	1.7	760	0.67

is particularly important in connection with distortion caused by iron cores. To demonstrate this, the writer measured the distortion across an iron-cored inductor connected to a generator giving either one or two sinusoidal signals (Fig. 4). First the harmonics of a single 60-c/s signal were measured; then the intermodulation products caused by signals at 60 c/s and 400 c/s in the amplitude ratio 4 : 1 and having the same combined peak amplitude as the single signal. The results are given in Table I.

Here the intermodulation/harmonic ratio is fractional. The impedance of the coil was varying over the 60 c/s cycle, causing distortion of the waveform at that frequency. But at 400 c/s the impedance of the coil was much higher; consequently the 400 c/s was not modulated in proportion to the 60-c/s distortion.

It must be remembered, too, that if there is a non-linear element somewhere in the middle of the unit being tested, the signal amplitude ratio at the input of that element may differ considerably from the ratio at the input to the unit, and the distortion amplitude ratios at its output may differ considerably from those measured at the output of the unit, as a result of frequency distortion before or after the non-linear element.

Standard Intermodulation Test

Two methods of intermodulation measurement have been sufficiently used and recommended to have achieved some degree of standardization. In the first, sometimes called the S.M.P.E. method,[8–11, 15, 20, 21] outlined in Fig. 5, the distortion is made to take place at a low frequency f_1 (say 100 c/s) and non-linearity is estimated by the extent to which a comparatively high frequency signal f_2 (say 1,000 or 4,000 c/s) of one quarter the voltage (12db down) is modulated by it. The distortion products occur at $f_2 \pm f_1$, $f_2 \pm 2f_1$, etc. If strictly carried out, the method indicates the total r.m.s. value of all these products, and so is analogous to "total harmonic distortion" measurement, for it makes no distinction between products of different order.* And because the kind of non-linearity that generates nth harmonic also generates intermodulation of the nth order, it is not surprising if, in general, the unpleasantness increases with the order of intermodulation[14] There does not yet seem to be any conclusive evidence on the precise relationship, but the S.M.P.E. method is open to the same criticism as unweighted total harmonic measurement. It also possesses other possible causes of discrepancy[12], such as the characteristics of the output meter.

Following the same line of thought as with harmonics, one naturally inquires about weighting. The claim has been made that intermodulation measurement is self-weighting.[17, 22] This can be investigated with the help of ref.[13] We assume that a signal $v = V\cos\omega t$ is applied to an element having a single non-linear term kv^n and a level frequency characteristic. Column 2 in Table II shows the ratio of harmonic amplitude to fundamental V. It is interesting to note that this value applies whether $V\cos\omega t$ is the only signal present or not. If next the signal applied is $v = V_1\cos\omega_1 t + V_2\cos\omega_2 t$, column 3 shows the ratio of the coefficient of the nth order intermodulation product, $\cos(\omega_2 t - n\omega_1 t) + \cos(\omega_2 t + n\omega_1 t)$, to V_2. The intermodulation/harmonic ratio is given in column 4. If V is identified as V_1 in the two-signal input, V_1/V goes out, and the ratios are as in column 5. Compared with the harmonics, the intermodulation products are weighted in direct proportion to their order, n. Since these ratios apply to both sum and difference products, they are multiplied by 2 in the S.M.P.E. method, which combines both.

The relative signal amplitudes just considered do not, however, present a fair comparison. A single signal used for harmonic distortion measurement should, to be comparable, have the same peak value as the double signal used for intermodulation. Column 6 therefore shows the ratios when $V = V_1 + V_2$. If, as in the S.M.P.E. method, $V_1 = 4V_2$ and the ratios are doubled, the results in column 7 show a weighting that begins feebly in the right direction and then reverses. The values for second and third order distortion agree with those calculated (and checked by experiment) in ref.[11] Distortion confined to the second order can be realized approximately in a single triode without negative feedback, and third-order distortion in a push-pull stage; but the other conditions (distortion of one order only, higher than the third) are artificial. In any case, fourth-order products are inevitably accompanied by much larger second-order products, fifth by third, sixth by fourth and second, and so on[13]; and these alter the ratios tabulated for second and third order, the tendency being to

* An intermodulation product of frequency $pf_1 \pm qf_2$, resulting from frequencies f_1 and f_2, is said to be of the $p+q$ order (but some writers refer to it as the $p+q-1$ order).

TABLE II

1	2	3	4	5	6	7
Order of distortion, n	**Relative harmonic amplitude**	**Relative intermod. amplitude**	**Intermod./harmonic ratio, R**	**R when $V = V_1$**	**R when $V = V_1 + V_2$**	**2R when $V = 5V_2$, $V_1 = 4V_2$**
2	$\frac{kV}{2}$	$\frac{2kV_1}{2}$	$\frac{2V_1}{V}$	2	$2\Big/\left(\frac{V_2}{V_1}+1\right)$	3.20
3	$\frac{kV^2}{4}$	$\frac{3kV_1^2}{4}$	$3\left(\frac{V_1}{V}\right)^2$	3	$3\Big/\left(\frac{V_2}{V_1}+1\right)^2$	3.84
4	$\frac{kV^3}{8}$	$\frac{4kV_1^3}{8}$	$4\left(\frac{V_1}{V}\right)^3$	4	$4\Big/\left(\frac{V_2}{V_1}+1\right)^3$	4.08
5	$\frac{kV^4}{16}$	$\frac{5kV_1^4}{16}$	$5\left(\frac{V_1}{V}\right)^4$	5	$5\Big/\left(\frac{V_2}{V_1}+1\right)^4$	4.08
6	$\frac{kV^5}{32}$	$\frac{6kV_1^5}{32}$	$6\left(\frac{V_1}{V}\right)^5$	6	$6\Big/\left(\frac{V_2}{V_1}+1\right)^5$	3.92

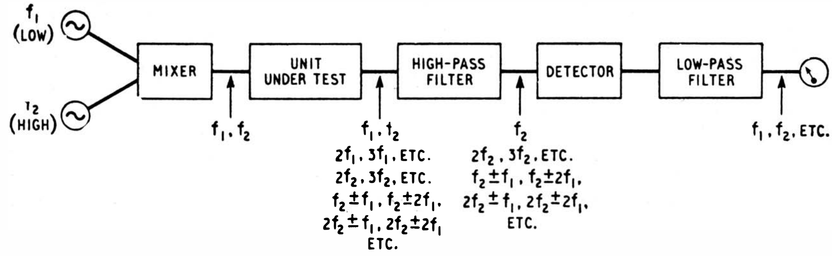

Fig. 5. Block diagram of the usual arrangement (S.M.P.E.) for measuring total intermodulation.

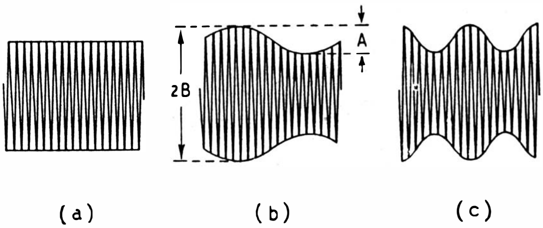

Fig. 6. Typical modulation envelopes showing (a) no distortion, (b) second-order distortion, (c) third-order distortion.

equalize the ratios. This is another fact that upsets the self-weighting theory.

Thus each different non-linear transfer characteristic has a different ratio of intermodulation to harmonics, and the ratio depends on whether the distortion products are measured separately or lumped together, but for practical non-linearities and no frequency discrimination it is fair to say that, as regards weighting, total intermodulation measurements show no advantage over harmonics. In fact, it is easy to see from Table II that if one uses signals of equal amplitude ($V_1 = V_2$) the weighting is the wrong way round!

The S.M.P.E. equipment has therefore been modified in various ways at the indicating end with a view to giving some degree of weighting to the higher-order products. In one variant[16] called the peak-sum method, the indicator measures the *peak* value of the modulation-frequency output instead of the r.m.s. or the mean-rectified. When only one modulation frequency is present (because the distortion is all second or third order) all three values are of course in fixed proportion to one another, but in all other cases the modulation-frequency output is non-sinusoidal and its peak value is equal to the sum of the peak values of all the separate distortion components—provided that at some phase their peaks all coincide. Even if they always did (and it does not appear that this can be guaranteed) the result does not really amount to weighting, for the increase in reading due to the addition of any distortion component is quite independent of its order.

In another modification[17], named after Le Bel but basically the same as that described much earlier by Bartlett[23], the indicator is a cathode-ray oscilloscope, which displays the modulated high-frequency signal without rectification, on a time base covering one cycle of the low-frequency signal, as in the usual c.r.o. method of measuring depth of modulation[24]. When there is no distortion the trace has a rectangular envelope as in Fig. 6(a). Second and third order distortion produce patterns such as (b) and (c) respectively. Le Bel reckons the distortion by adding up the depths of all the " notches," such as A, in the pattern, counting both top and bottom. The sum of all the notch depths—two in (b) and four in (c)—is divided by B and expressed in per cent. Third-order distortion therefore counts twice as much as second-order distortion causing the same depth of modulation. This seems to contradict a graph given with the original description of the method, connecting the notch-depth percentage with the unweighted S.M.P.E. intermodulation percentage, and stated to apply to amplifiers of all types. It should be noted that notch depth (A/B) is not the same as depth of modulation (which is A/(2B-A)) except at 100%; at low values it is nearly twice as great, not counting the additional doubling when the bottom notch is included. The weighting is a step in the right direction, but bears no simple relationship to the systems mentioned in connection with harmonics. Unless the c.r. tube is of a precision type and the pattern is carefully measured, the method is not suitable for testing modern low-distortion equipment.

Incidentally, the ratio of between 3 and 4 when measuring total intermodulation with a 4 : 1 signal ratio as in the S.M.P.E. method is sometimes quoted[8] as ground for saying that such measurement is more sensitive than harmonic measurement. But it has been shown[11] that with some kinds of non-linearity the ratio may be as low as 1; and in any case the intermodulation percentage is reckoned with reference to a signal of only one fifth the amplitude that would be used for harmonic measurement, so this supposed advantage is illusory.

Another Standard Method

Quite different from the S.M.P.E. method is the C.C.I.F. method[25, 18]. The input signals are equal in amplitude and differ in frequency by a constant frequency; it is the single distortion product at this difference frequency that is measured. The great advantage of this method is that distortion can be measured over the whole frequency band. On the other hand, only second-order distortion is measured. So, for example, a well-balanced push-pull amplifier would be made to appear almost distortionless, notwithstanding that it might have severe odd-order distortion, in which case one's ears would flatly contradict the instrument reading. The measuring instrument is preferably a wave analyser, which however need not operate at more than one or two fixed frequencies. Since neither of the two signals is stronger than the other, the frequency at which the distortion is being made to occur is ambiguous.

It is clear that (notwithstanding suggestions to the contrary) no one of all these many methods of measuring non-linearity distortion can be relied upon to give readings in agreement with listening tests, unless some restrictions are placed on the nature of the items tested. For testing iron-core transformers, Williams and Eastop[26] prefer harmonic measurements to intermodulation, because there are fewer variables and correlation is as good; for film and disk recording, the S.M.P.E. intermodulation method has become firmly established[10, 15, 21]; for hearing aids both these methods are regarded as useless and the C.C.I.F. method strongly advocated[18].

Suitability of Methods

What do we conclude from all this? Surely that the method or methods chosen must be those that experience has shown to agree with aural judgment, over the whole range of equipment to be tested and the whole range of distortion liable to occur in it. Thus, for routine tests of similar units in which the kind of distortion is unlikely to vary and one only wants to check that the amount is tolerable at a specified level, quite a simple total harmonic or intermodulation system may do. If the kind of distortion *is* liable to vary, then a weighted system would be preferable. An advantage of a total system is that it can be applied where (as sometimes in reproduction from records) the frequency is not constant enough for wave-analyser readings. On the other hand, during development of new equipment, in which every possible kind of distortion must be investigated before final approval—and especially where different kinds of equipment are developed—it is necessary to have apparatus capable of separately measuring all the distortion components under any desired conditions; in other words, at least a generator producing two signals variable over the full frequency range, and a wave analyser. Such equipment is somewhat expensive, but it is proposed to describe in a future issue apparatus capable of a wide range of reasonably accurate measurements and of being constructed at moderate cost.

For investigating distortion at low frequencies, the choice lies between measuring the harmonics of a single signal at that frequency or the modulation by it of a relatively high-frequency low-amplitude signal. As regards the signal generator, the advantage of needing only one signal for harmonics must be considered against the advantage of needing less extremely pure waveform in the two required for modulation. As regards output-measuring equipment, if total unweighted values are required the balance between harmonics and intermodulation is perhaps fairly even. But a weighted total reading is more easily obtained for harmonics. Separate measurement of each order of distortion necessitates a more selective wave analyser for modulation than for harmonics, but the frequency characteristic of the unit under test is less likely to affect the relative amplitudes, and the distortion measured can be at more audible frequencies.

At high frequencies, neither system yields a series of distortion products, corresponding to the different orders, within the a.f. band. But if there is second-order distortion, beating between upper frequencies is audibly objectionable, and this is where the C.C.I.F. method (or something like it) is valuable. In recording and f.m. systems, the amplitude of the high frequencies is increased by pre-emphasis, and any overloading at these frequencies yields distortion products at lower frequencies, which are not reduced by the subsequent de-emphasis so become relatively more prominent.

At medium frequencies no particular method is always the best, and choice depends on circumstances.

While the need for versatility and flexibility thus seems to exclude all hope of standardization, there ought not to be a greater variety of test conditions than is really necessary. The writer would like to suggest that, except where special circumstances indicate otherwise, a fixed distortion-product frequency somewhere in the most audible part of the band (say 1,000-2,000 c/s) should be adopted. A fixed frequency simplifies apparatus and operation, and removes one of the biggest sources of disagreement between meter readings and aural appraisal—their widely dissimilar frequency characteristics. Choice of a middle frequency ensures that what is read is actually highly audible distortion, even though it may be generated by tones of relatively low audibility.

For example, suppose the chosen frequency is 1,320 c/s (this rather odd choice was to minimize the risk of spurious responses). Then Table III shows typical (but not necessarily the best possible) input frequencies for measuring the distortion at representative points in the a.f. band. Adoption of the widely used 4 : 1 amplitude ratio is recommended, because it leads to distortion that is predominantly at the frequency of the stronger signal, and does not discriminate against the higher orders like equal signals.

Although he may in that respect be unfashionable, the writer refrains from making the claim that the scheme he recommends gives complete correlation between measurements and audible distortion, but does suggest that it may be less liable to be " caught out " by particular circumstances than some for which such claims have been made.

Perhaps the most instructive form in which the results of measurements according to such a scheme can be presented is as graphs (one for each strong-signal frequency) showing as separate curves the variation of each distortion product with output power. There is some evidence[14] that the point where odd-order intermodulation starts a rapid rise corresponds to the onset of audible distortion. Whether this generalization is valid or not, it is important that any distortion data should bring out two things: (1) Whether the distortion is mainly second or third, and (2) Whether the series converges rapidly (so that products above the third are negligible) or slowly (so that there are appreciable quantities of the higher orders, indicating some sharp curvature in the transfer characteristic).

In equipment in the high fidelity class, products higher than the third ought to be negligible, so particulars of distortion in its specification would normally be much less formidable than Table III might suggest. Along with the assurance that all higher-order modulation is less than 0.?% it should

TABLE III

Order of modulation product	Frequency of weak signal when strong signal frequency is:			
	65 c/s	800 c/s	3,000 c/s	12,000 c/s
1 (fundmtl.)	1,320	1,320	1,320	1,320
2	1,385	2,120	4,320	13,320 (or (10,680)
3	1,450	2,920	7,320	
4	1,515	3,720	10,320	
5	1,580	4,520	13,320	
6	1,645	5,320	16,320	
7	1,710	6,120	19,320	

be sufficient to give the percentages of second and third at two suitable frequencies. Some substantial improvement on present practice need not therefore be completely unpractical.

REFERENCES

[1] "Cathode Ray," "Distortion" and "More Distortion," *Wireless World*, April, May, 1955, p. 191, p. 239.
[2] Tyler, V. J., "Simple distortion meter," *Wireless World*, Sept. 1953, p. 431.
[3] Wigan, E. R., "Diagnosis of distortion," *Wireless World*, June 1953, p. 261. See also [4].
[4] Pressey, D. C., "Measuring non-linearity," *Wireless World*, Feb. 1954, p. 60.
[5] B.S.2065: 1954. *Glossary of Terms for Characteristics of Radio Receivers*, Defn. 319.
[6] Radio Manufacturers' Association, "Specification for testing and expressing overall performance of radio receivers," 1936. (Reproduced in *Proc. Wireless Section I.E.E.*, Sept. 1937, p. 12).
[7] Shorter, D. E. L., "The influence of high-order products in non-linear distortion," *Electronic Engineering*, April 1950, p. 152, and correspondence Oct. 1950, p. 443 and July 1951, p. 278.
[8] Hilliard, J. K., "Distortion tests by the intermodulation method," *Proc. I.R.E.*, Dec. 1941, p. 614, and discussion, Sept. 1942, p. 429.
[9] Roddam, T., "Intermodulation distortion," *Wireless World*, April 1950, p. 122.
[10] Frayne, J. G., and R. R. Scoville, "Variable density recording," *J. Soc. Motion Pic. Eng.*, June 1939, p. 648.
[11] Warren, W. J., and W. R. Hewlett, "An analysis of the intermodulation method of distortion measurement," *Proc. I.R.E.*, April 1948, p. 457.
[12] Berth-Jones, E. W., "Intermodulation Testing," *Wireless World*, June 1951, p. 233.
[13] Callendar, M. V., and S. Matthews, "Relation between amplitudes of harmonics and intermodulation frequencies," *Electronic Engineering*, June 1951, p. 230.
[14] Harries, J. H. O., "Amplitude distortion," *Wireless Engineer*, Feb. 1937, p. 63.
[15] Roys, H. E., "Intermodulation distortion analysis as applied to disk recording and reproducing equipment," *Proc. I.R.E.*, Oct. 1947, p. 1,149.
[16] Fine, R. S., "An intermodulation analyzer for audio systems," *Audio Engineering*, July 1950, p. 11.
[17] Le Bel, C. J., "A new method of measuring and analyzing intermodulation," *Audio Engineering*, July 1951, p. 18.
[18] Peterson, A. P. G., "Intermodulation distortion," *General Radio Experimenter*, March 1951, p. 1.
[19] Scott, H. H., "Intermodulation measurements," *J. Audio Eng. Soc.*, Jan. 1953, p. 56.
[20] Hilliard, J. K., "Intermodulation testing," *Electronics*, July 1946, p. 123.
[21] Read, G. W., and R. R. Scoville, "An improved intermodulation measuring system". *J. Soc. Motion Picture Engineers*, Feb. 1948, p. 162.
[22] Sturley, *Radio Receiver Design*, 1st edn., Part 2, p. 82.
[23] Bartlett, A. C., "Inter-modulation in audio-frequency amplifiers," *Wireless Engineer*, Feb. 1935, p. 70.
[24] Van Beuren, J. M., "Simplified intermodulation measurements," *Audio Engineering*, Nov. 1950, p. 24.
[25] *Proc. C.C.I.F.*, 1936, p. 684.
[26] Williams, T., and R. H. Eastop, "Harmonic distortion in iron-core transformers, *Audio Eng*. April 1951, p. 18.

LETTERS TO THE EDITOR

The Editor does not necessarily endorse the opinions expressed by his correspondents

Transistor Letter Symbols

FURTHER to D. Nappin's letter (your May issue) on this subject, the inter-service symbol for a switch has for some years been the letters SW. Recently, however, this has been modified by BS530 (Supplement No. 1 amended) which lists "mandatory designations" and "designations normally used" in Tables 1 and 2 respectively. The latter table lists the letter S for a switch.

I, personally, favour the suggestion put forward by Mr. Thompson (in the same issue). The letter Y is so far not in use in the Tables referred to above, and the similarity to the circuit symbol is a very good argument for its adoption.

Signals Research and Development Establishment. K. J. NEIGHBOUR.

SINCE the thermionic tube was given the name of "valve" because it would not permit a reverse flow of electrons, and since a transistor, properly used, has the same characteristic, it seems to have the same claim as the former to the word "valve" and hence to the symbol V. The Americans, of course, have no problem. For them tubes, with a T, are being replaced by transistors, also with a T. No doubt those amongst us whose valves have "plates" fed from "rails" and control grids apparently made of corrugated iron will follow in this also.

College of Technology, Manchester. V. MAYES.

F.M. Receiver Design

I AM surprised that M. R. Murray in his contribution on the ratio detector on page 245 of your May, 1955, number made no reference to an article on f.m. reception by D. Maurice and R. J. H. Slaughter in the March, 1948, issue of *Wireless World* (page 103).

This latter article gives a convincing but simple explanation of the suppression of unwanted amplitude modulation. I am afraid Mr. Murray did not convince me that his unbalanced circuit was capable of the necessary suppression. The statement is made that the a.f. output follows the ratio $V_{K''d}/V_{a'''d}$. This statement is not substantiated nor are its consequences followed up.

I disagree with his statement that with a suitably designed circuit the ratio $V_{k''d}/V_{a'''d}$ follows *faithfully* the original audio modulation. This is only true when second and higher orders of small quantities are neglected.

Malvern, Worcs. F. L. MORRIS.

I FAIL to understand why Messrs. Amos and Johnson should choose the ratio detector for their f.m. receiver[1]. While saving a valve may be of prime importance to a set maker, it should surely not be decisive to the home constructor. It seems illogical to save a valve at the cost of trebling the distortion (on the figures quoted in the article) and feed the output, as most will be doing, into a high-quality amplifier in which no expense has been spared to get the distortion down to the 0.1% level. Or is there some mystic reason why 3% in the detector does not matter, but 3% in the output stage does (perhaps "Cathode Ray" can enlighten us?). Incidentally, what has happened to Thomas Roddam's circuit[2]? Does it really work?

Redhill, Surrey. J. K. CARTER.

Proprietorship of Band III

ON May 11 it was announced that the B.B.C. have ordered transmitting equipment to enable them to start a second television programme on wavelengths in Band III.

Declaring my interest in one of the programme contractor companies (Associated-Rediffusion, Ltd.), I wrote

[1] Amos & Johnstone; *Wireless World*, April 1955.
[2] Roddam; *Wireless World*, July 1948.