

The Influence of High-Order Products in Non-Linear Distortion

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THE commonly accepted figures for the maximum allowable non-linear distortion in broadcasting and reproducing systems are based on work carried out many years ago. Since then, new kinds of apparatus producing forms of distortion not covered by the early experiments have come into use, with the result that subjective assessments of non-linear distortion do not always agree with assessments based on measurement. This article describes some recent experiments showing the extent of the error which can result from the common practice of taking the R.M.S. total harmonic distortion of a system as a criterion of linearity.

Comparative tests were carried out on six different systems, which are designated in the Tables by the letters A to F. The distortion introduced by each system varied only slightly with signal amplitude up to a fairly well defined overload point, and the investigation was confined to signals not exceeding this amplitude. In four of the systems (A, B, C, F) the principal distortions were substantially constant over most of the frequency range, and in the other two (D and E) the application of negative feed-back had reduced the distortion over the lower part of the frequency range, without appreciably affecting it for frequencies of 1,000 c/s. and above. With these last two systems, therefore, the standard of quality was set by the distortion of signals above 1,000 c/s., and since most programme material has from time to time a large proportion of its energy around and above this frequency, valid comparisons of *maximum* distortion could still be made between the various systems.

Subjective assessments of non-linear distortion were made on the six systems by listening to a programme on a wide-range coaxial-horn loudspeaker. Much of the test programme consisted of solo pianoforte, the reproduction of which has been found to be seriously impaired by quite a small amount of non-linear distortion. An immediate comparison was made by listening to the programme reproduced through a transmission circuit having very low inherent distortion, the system under investigation being periodically introduced into the chain.

Objective assessments of the non-linearity were made in the first instance by measuring the R.M.S. sum of distortion products produced by the application of either a single tone or of two tones together. It soon became evident, however, that a more detailed analysis was called for, and eventually a single test tone was used with a wave analyser capable of indicating distortion products as small as 0.01 per cent of the fundamental. In addition, the input and output of the system under test were applied to the X and Y plates of a cathode-ray oscilloscope, the phase of the input being adjusted to produce a line. The oscillogram was then examined for sharp bends or

kinks, which would indicate the presence of high-order harmonics. The input frequency used for the harmonic distortion measurements was 250 c/s. for systems A, B, and C, and 1,000 c/s. for systems D, E, and F.

TABLE I

| System | Subjective Classification of Distortion | R.M.S. Sum of Harmonics |
|--------|---|-------------------------|
| D | Bad | 3.7% |
| B | Perceptible | 3.3% |
| C | Just perceptible | 2.6% |
| A | Bad | 2.3% |
| E | Just perceptible | 0.62% |
| F | Not perceptible | 0.41% |

Table I shows the rough subjective assessment of the distortion of the six systems, alongside the R.M.S. total harmonic measured at a level 8 db. below the overload point. The systems are tabulated in decreasing order of harmonic distortion, and it will be seen that there is poor correlation between the subjective assessment of distortion and the total harmonic measurement.

The oscillograms for systems A and D showed pronounced kinks, suggesting the presence of high-order harmonics, and similar though less prominent discontinuities were displayed by system E. That high-order harmonics are more offensive than low has long been recognised, and it was thought that if allowance for this factor were made, the discrepancies of Table I might be accounted for. The amplitude of each measured harmonic was therefore weighted by a factor proportional to its order relative to the second, a procedure laid down as long ago as 1937 in an R.M.A. specification† for testing broadcast receivers, but, as far as it is known, not widely adopted. According to this procedure, the amplitude of the n th harmonic is multiplied by $n/2$, so that the figure for the 2nd harmonic is unchanged. The result of this weighting is given in Table II, in which the systems

TABLE II

| System | Subjective Classification of Distortion | R.M.S. Sum of Harmonics with n th Harmonic Amplitude multiplied by $n/2$ |
|--------|---|--|
| D | Bad | 6.7% |
| A | Bad | 5.1% |
| B | Perceptible | 5.1% |
| C | Just perceptible | 2.8% |
| E | Just perceptible | 1.3% |
| F | Not perceptible | 0.8% |

are again presented in decreasing order of the distortion figure. It will be seen that the balance is now partially redressed, but that, contrary to the subjective assessment, systems A and B appear to be equally bad.

A more drastic weighting, in which the amplitude

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† "Specification for Testing and Expressing Overall Performance of Radio Broadcast Receivers—Part 2—Acoustic Tests." Published by the Radio Manufacturers' Association. Revised December, 1937. See page 5 under "Distortion Factor."

of the n th harmonic is multiplied by $n^2/4$, was therefore tried. The result with this weighting, which again leaves the 2nd harmonic unaffected, is given in Table III. This time, the order of merit obtained

TABLE III

| System | Subjective Classification of Distortion | R.M.S. Sum of Harmonics with n th Harmonic Amplitude multiplied by $n^2/4$ |
|--------|---|--|
| A | Bad | 19.4% |
| D | Bad | 16.5% |
| B | Perceptible | 8.6% |
| E | Just perceptible | 4.5% |
| C | Just perceptible | 3.3% |
| F | Not perceptible | 2.2% |

from the distortion figures confirms that obtained by subjective tests, and the difference between systems A and B is clearly brought out.

The series of figures resulting from this heavy weighting of harmonic amplitudes converges very slowly if at all, so that the total distortion figure depends to some extent on the number of terms taken. It is therefore desirable to place some limit on the number of weighted harmonics that are included in the total. One method is to include only harmonics up to a certain order. This method was tentatively applied by excluding all harmonics above the 15th, but was ultimately rejected because the results discriminated in favour of the worst system, such as A, which had 0.03 per cent of 25th harmonic. Since heavy weighting brings into prominence some components which were initially too small to be accurately measured, it may be preferable rather to exclude all harmonics having less than a certain amplitude. This criterion was applied to the present data, all terms based on harmonic figures of less than 0.03 per cent being excluded as insufficiently accurate.

The importance of high-order harmonics, even when individually small in energy content, suggests that distortion should be regarded in terms not so much of the separate harmonics as of the complete series or of

the composite wave-form that this series represents. The properties of the wave-form which are significant for this purpose remain to be investigated. It may be noted, however, that the product obtained by weighting the distortion wave-form proportionally to the square of the frequency, i.e., by adding 12 db. per octave rise, or differentiating twice, gives a measure of the reciprocal of the radius of curvature of the wave-form, and is therefore related to the sharpness of any corners on it.

The type of input-output characteristic which produces many high-order harmonics from a single-frequency tone will also produce a large number of inter-modulation products when several tones are simultaneously applied. For example, where a single tone of frequency p would produce a single harmonic $2p$, two tones of frequencies p and q would produce two sum and difference frequencies, $p \pm q$. Similarly, a harmonic $3p$ originating from a single tone corresponds to four inter-modulation products ($p \pm 2q$, $2p \pm q$) from two tones, a harmonic $4p$ to six inter-modulation products and so on. Consequently, when the amplitude characteristic of a transmission system has a sharp discontinuity, the number of alien frequencies generated during the transmission of a programme must be very large. It is therefore important that this form of distortion should be recognised whenever it occurs, and also that objective tests should be so framed that they give appropriate numerical expression to its effects. Much speculation is possible as to the best way of achieving this end, but there is as yet insufficient evidence to justify the use of any one formula. The results of the experiments described above show the danger of designing equipment to the usual figure of total harmonic distortion without reference to the type of non-linearity concerned. The time appears ripe therefore for the early experiments on permissible distortion limits to be repeated, taking into account all forms of non-linearity known to occur in modern systems of sound transmission and reproduction.

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