A New Method of

Measuring and Analyzing Intermodulation

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The oscillographic method is developed to give quantitative results, based upon the experimentally found relation between total notch depth and IM percentage.

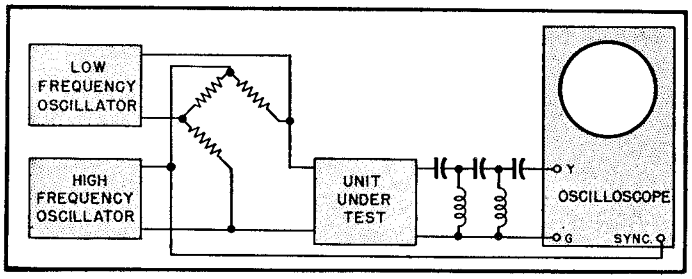

Fig. 1. Typical intermodulation analysis circuit.

THE INTERMODULATION MEASURING DEVICE to be discussed is a quantitative development of an oscillographic method hitherto considered only qualitative in nature. In the course of the research, gross inaccuracy was found in the traditionally accepted 4:1 relationship between intermodulation and harmonic distortion.

Intermodulation meters built according to Hilliard's design[1] have had provision for connecting an oscilloscope into the circuit, but the first published study of oscilloscope images in distortion measurement may be credited to McProud.[2]

Harmonic vs. Intermodulation Distortion—A Review

In typical audio applications, distortion measurement must yield a number which bears some relation to the offensiveness of the sound to the ear—for audio equipment is usually made to be listened to.

By this test, the harmonic method of measuring distortion may be unsatisfactory. It fails to indicate the bad effect of polishing a disc master, while the intermodulation method succeeds. The writer has found that poor tracking (of a phonograph pickup stylus in its groove) may produce hardly any effect on harmonic distortion, while the intermodulation and the aural effect rise greatly.

The harmonic method may be satisfactory if we measure the relative amplitude of the individual harmonics, then multiply each by a weighting factor. This requires a wave analyzer, whose use is tedious and time consuming; and little has been published on the weighting factors which would equate the order of a harmonic and its offensiveness to the ear. An early step was the 1937 RMA proposal[3] according to which the amplitude of the *n*th harmonic would be multiplied by *n/2*, which leaves the second harmonic unchanged. A more recent proposal was made by Shorter,[4] who proposed a weighting in which the amplitude of the *n*th harmonic would be multiplied by $n^2/4$, and in which harmonics weaker than .03 per cent would be neglected.

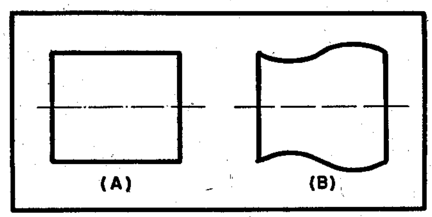

Fig. 2. Envelope of oscilloscope images without intermodulation (A), and with intermodulation (B).

A fundamental problem of the harmonic method is that of achieving a pure waveform at the input to the equipment under test, for the harmonic measuring device cannot distinguish between an imperfection of the source waveform and one produced by the unit being tested. At any *one* frequency, pure waveform can be achieved by an inexpensive filter, but when testing over a wide frequency range the pure waveform source becomes more expensive than the distortion meter itself.

The intermodulation method presents no such waveform problem, for the waveform of ordinary laboratory oscillators

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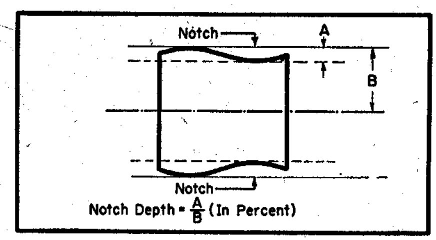

Fig. 3. Definition of notch depth.

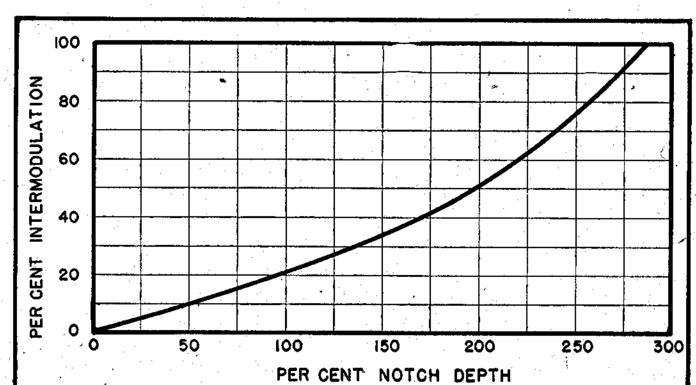

Fig. 4. Relation between notch depth and per cent intermodulation.

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[1] John K. Hilliard: Distortion tests by the intermodulation method. *Proc. I.R.E.*, vol. 29, no. 12, pp. 614–620, Dec. 1941.

[2] C. G. McProud: Simplified intermodulation measurement. AUDIO ENGINEERING, vol. 31, no. 3, pp. 21–23, May 1947.

[3] Radio Manufacturers Association: Specification for testing and expressing overall performance of radio broadcast receivers—Part 2—Acoustic tests;—p. 5; Dec. 1937 revision.

[4] D. E. L. Shorter: The Influence of High Order Products in Non Linear Distortion. *Electronic Engineering*, vol. 22, no. 266, pp. 152–153, April 1950.

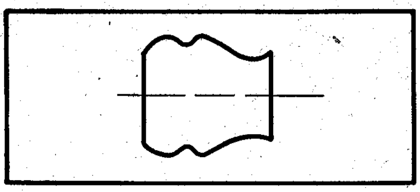

Fig. 5. Envelope of notch pattern with insufficient bias, for single-ended stage.

is satisfactory, and it is easy to mix two tones without creating the intermodulated source tone that would be a cause of error.

The intermodulation method was first used extensively in the film industry, after the harmonic method had failed to serve as a satisfactory guide to the ear's opinion of film distortion. Roys has made extensive use of intermodulation in various problems of disc recording and reproducing. He has shown that it is a reliable index to processing faults[5] where the harmonic method is valueless, and is also very useful in judging the tracking of disc reproducers[6] and in studying tracing distortion.

We may theorize that the intermodulation method more nearly correlates with the ear's opinion because the result is automatically weighted by the order of the distortion. There has been little attention to this, and it would be a real contribution to the art if someone were to study the action of high order distortions. From Frayne and Scoville's work it is evident that the weighting for higher distortion orders could be increased, if desired, by using a higher ratio of low- to high-frequency voltage than the four to one which is customary. A ratio of eight or ten to one would be worth studying.

It may readily be concluded that the intermodulation method deserves more intensive use than has been customary. One cause of the neglect has been the high cost of intermodulation measuring instruments; another has been the lack of realization of the value of oscilloscope images as a guide to corrective measures.

A New Method of Measuring Intermodulation

As may be observed, the following method deviates from prior practice only at the finish:

1. Mix two tones of different frequency, without intermodulation, in any standard circuit. Bridge networks and hybrid coils are the most obvious means.
2. Pass the two-frequency tone through the system under test.
3. Send the system output through a high-pass filter, which removes the lower of the two frequencies. A typical circuit is shown in *Fig. 1*.
4. Observe the filter output on an oscilloscope whose sweep is synchronized to the *low*-frequency tone.
   - A. If the high-frequency tone is not modulated by the low-frequency tone (i.e., a condition of zero intermodulation), the oscilloscope screen will show a smooth rectangle of light, like (A) of *Fig. 2*.
   - B. If one tone affects the other (by definition an intermodulation condition), the rectangle of light will be marred by one or more notches, as in (B) of *Fig. 2*.
5. There is a quantitative relation between the size of the notches and the intermodulation percentage. Each notch has a *notch depth,* which is defined in *Fig. 3*, and which is best expressed in per cent. An image of this type will generally have more than one notch, each with its own depth. The following relation is then used:

Total notch depth = Notch_1 depth + notch_2 depth + etc. This may lead to a total notch depth of over 100 per cent if each notch depth is expressed in per cent.

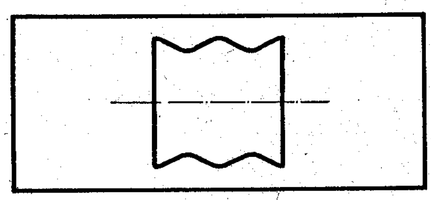

Fig. 6. Normal notch pattern for push-pull stage.

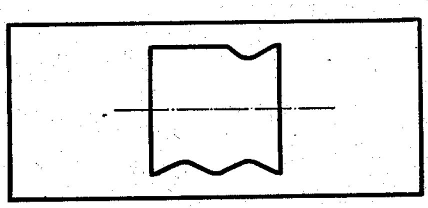

Fig. 7. Push-pull output stage with single-ended driver stage showing effect of driver overload.

The relation between total notch depth and intermodulation percentage is shown in *Fig. 4*. This was experimentally determined, using an intermodulation meter similar to that shown by Hilliard,[1] and typical experimental points are shown on the figure. The following types of amplifiers were used in various combinations: single-ended and push-pull, triodes and pentodes, voltage amplifier and power amplifier tubes, with and without negative feedback. All conform to the same curve within the limits of experimental error.

Since this relation is linear over the most important part of the range—the lower part—it is possible to use an oscilloscope screen with suitable calibration, reading the intermodulation effect of each notch directly on the scale. In the less used upper part of the range, the same screen scale may be used in conjunction with a corrective graph.

Analysis of Oscilloscope Patterns

The oscilloscope screen may show a variety of patterns. In a single-ended stage either two or four notches in the pattern will ordinarily appear, depending on conditions. If the bias is too low, two narrow notches may appear toward one side of the patterns as in *Fig. 5*. If the grid is driven heavily toward cutoff, broader notches will appear toward the opposite side of the pattern. We have not used the words "right" and "left" to refer to notch position because the position depends on the number of amplifier stages and on the oscilloscope circuit. In a simple single-ended circuit with the most common oscilloscope characteristic, bias notches will be at the left side; and notches due to grid cutoff at the right side. If an amplifier is heavily overdriven, both bias and cutoff notches may appear—four in all.

In a push-pull stage, four notches are standard, as in *Fig. 6*; and in a perfectly balanced stage, the notches are equal in size. If the push-pull stage is driven by a single-ended stage which overloads easily, one of the notches will diminish in size and may even disappear, as in *Fig. 7*.

The fact that these notches occur on top or bottom of the pattern indicates that intermodulation can occur on either positive or negative half cycle of the high-frequency wave. Since the notches are not necessarily symmetrical, it becomes clear that the rectifier in an intermodulation meter must be full wave —else it may ignore intermodulation effects occurring in the half cycle which is not rectified.

This is sufficient to indicate the general nature of the information provided by the notches; a full description of the subject would be a paper in itself.

It has been customary to make most intermodulation tests with a **4:1 ratio of** low- and high-frequency voltages. This

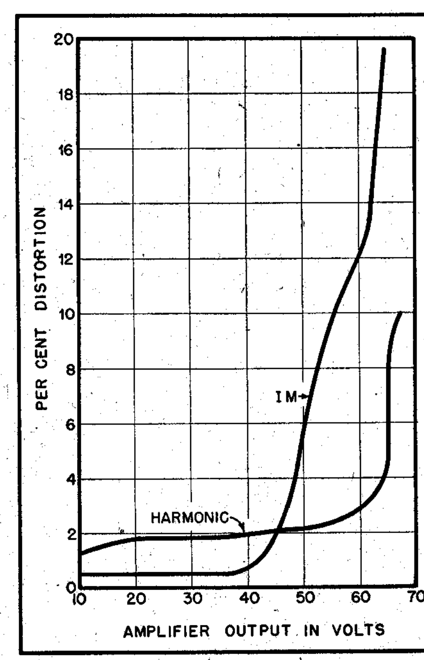

Fig. 8. Intermodulation (IM) and harmonic distortion characteristics of a push-pull amplifier showing that the ratio of the two parameters changes.

[5] H. E. Roys: Intermodulation distortion analysis as applied to disc recording and reproducing equipment; *Proc. I.R.E.*, vol. 35, no. 10, pp. 1149-1152, Oct. 1947.

[6] H. E. Roys; Determining the Tracking Capabilities of a Pickup; AUDIO ENGINEERING, vol. 34, no. 5, pp. 11 & 38–40, May 1950.

can lead to results of doubtful significance if applied universally—a matter which is evident from a brief consideration of the physical relationships involved. For example, if we use a test tone of 40 and 20,000 cps, in 4:1 ratio, with most amplifiers there will be real doubt as to whether low-frequency distortion or high-frequency distorton predominates in the measurement. If results are to have any significance, separate measurements of low- and high-frequency conditions must be made.

Applying this thought, low-frequency distortion should be checked by using a low frequency of 40 or 60 cps, and a high-frequency condition which would have relatively no distortion tendency. This might be a high frequency of 2000 cps, and a voltage ratio of 4:1. Thus the high frequency would be primarily an indicator.

A high-frequency measurement should be made with 7000 or 12000 cps and a low-frequency condition which would have minimum distortion tendency. This could be a low frequency of 100 or 200 cps, and a voltage ratio of 1:1.

A number of papers have compared the intermodulation method with the two-tone or CCIF method, claiming that the latter has a greater sensitivity to high-frequency distortion. We are inclined to attribute their result, instead, to the fact that they tried, unwisely, to measure high-frequency distortion with a low-frequency tone of four times the amplitude of the high frequency of which they were trying to determine the effect.

Background

The examination of oscilloscope images in conjunction with intermodulation tests was first suggested by Hilliard[1] in 1941, but he supplied no data on the types of images to be expected, and their meaning, so very little American use was made of the idea. Some European use was begun, however. McProud in 1947 described the use of screen images for distortion analysis, but stated that the relation between notch size and per cent intermodulation was only qualitative. As applied to any single notch, in McProud's fashion, this is correct. but when applied to the total notch depth as we have (a method not contemplated by McProud) his statement is in error.

In our experiments we observed a new effect: The oscilloscope pattern occasionally shows bulges instead of notches, a sign of regeneration, it may occur in multi-stage amplifiers if isolation and filter condensers are insufficient, or if an improperly designed feedback loop has been utilized. It seems to occur most often in the 5- to 35-cps range, and explains why some units test satisfactorily under conventional conditions, yet sound bad with low-frequency program material.

Relations between IM and Harmonic Distortion

It has been customary to assume that a fixed ratio exists between the intermodulation distortion and the harmonic distortion produced at the same operating point. Thus Frayne and Scoville[7] in 1939 gave formulas which, for the usual four to one ratio of low- and high-frequency intermodulation inputs, gave intermodulation as 3.2 times the harmonic distortion for second order distortion. They concluded that the overall relation was 3.8 times.

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Hilliard[1] in 1941 originated the statement that the ratio was *approximately* four times. Unfortunately, the word "approximately" was lost when the phrase transferred to the engineering world's memory, so most engineers have incorrectly assumed a rigid four times ratio.

Warren and Hewlett in 1948 analyzed the relationship at greater length. For the distortion law they first assumed, the ratios became 3.2 times for single-ended stages, and 3.8 times for push-pull operation, but if another assumed distortion law were followed, they found that the ratio might drop to unity.

In 1950 Roddam[8] assumed still another distortion law and found a 2.8 ratio for second order distortion. In the same year Callendar[9] observed that tests on various tubes under various Class A and AB conditions gave ratios which did not agree well with computed values.

In a series of very interesting and significant observations on various amplifiers Pappas[10] has observed ratios all the way from over 6 down to less than unity.

That the ratio can change under various operating conditions is shown by *Fig.* 8, which illustates the performance of an ordinary push-pull amplifier with single-ended driver stage.

It is evident from *Fig.* 8 and the other data that no generalized relation exists between intermodulation and harmonic distortion. Under limited conditions a given ratio may apply, but its validity is very narrow in scope. The "four times" ratio is a dangerous error, and should be discarded from engineering thinking.

Conclusions

A new method of intermodulation measurement has been shown, involving much lower equipment cost and clearer illustration of equipment faults than has heretofore been possible.

It has been found that the traditional "four times" relation between intermodulation and harmonic distortion is of very limited significance. The only way to determine intermodulation distortion with certainty is to measure it.

[7] J. G. Frayne and R. R. Scoville: Analysis of measurement of distortion in variable density recording; *J. Soc. Mot. Pict. Eng.*, vol. 32, pp. 648–673, June 1939.

[8] Thomas Roddam; Intermodulation distortion; *Wireless World,* vol. 46, no. 4, pp. 122–125, April 1950.

[9] M. V. Callendar; The influence of high-order products in non-linear distortion; *Electronic Engineering,* vol. 22, no. 272, p. 443, Oct. 1950.

[10] P. Pappas: Electronic Development Laboratory, New York, private communication, 1950.