Correlation Audio Distortion Measurements*

EERO LEINONEN AND MATTI OTALA

Technical Research Centre of Finland, Electronics Laboratory, SF-90101 Oulu 10, Finland

The sensitivity of five audio distortion measurement methods is investigated by experimental measurements on circuits which simulate five basic distortion mechanisms. The results show that the ordinary methods of measuring total harmonic distortion and intermodulation distortion do not reveal dynamic distortions, and that every method has unacceptably low sensitivity for at least one distortion mechanism. The combined use of the dynamic intermodulation method and the two-tone difference frequency method for a complete specification of amplifier distortion is recommended because their "blind spots" do not overlap.

Distortion measurements on 11 commercial power amplifiers and 11 operational amplifiers have shown a mixture of the basic distortion mechanisms, mostly dynamic distortions for the operational amplifiers, and mixed static and dynamic distortions for the power amplifiers. In addition, more complex distortion mechanisms have been noted in the power amplifiers.

The results obtained by the different methods have been found to correlate qualitatively but not quantitatively for each type of basic nonlinearity separately. For mixed nonlinearities and in the case of commercial amplifiers the qualitative correlation disappears, and there seems to be no reliable way of predicting the measurement results of one method from that of another method.

INTRODUCTION: Distortion in audio equipment is presently measured and specified by two main methods, the total harmonic distortion measurement method (THD) and the standardized intermodulation distortion measurement method (SMPTE-IM) [1]. It is a widespread experience that low distortion values, as measured with these methods, are necessary but not sufficient requirements for acceptable sound quality. Recently a number of experimental measurements have been published [2], showing that under certain conditions and certain drive signals, commercially available amplifiers may show gross distortion which remains undetected with these methods.

Consequently new and more general measuring methods have been proposed for audio use. These include the two-tone difference-frequency distortion method (CCIF-IM) [1], which was originally intended for carrier-frequency telephony measurements, the dynamic intermodulation measuring method (DIM) [2], [3], and the noise transfer method [4], [5]. It has also generally been speculated that these new methods should yield qualitative, albeit not quantitative, correlation with each other in cases of strong dynamic intermodulation distortion. Here the term dynamic intermodulation is used to denote those distortions which depend not only on the amplitude characteristics of the signal, as is the case with static distortions such as low-frequency harmonic distortion, but also on its time properties [6].

It is the purpose of this paper to establish the correlation between measurement results obtained with all the methods mentioned, as well as to explain the reasons for the different sensitivities and the different "blind spots" inherent in these methods.

MEASUREMENT METHODS

In order to study the sensitivity of the different measurement methods to different basic distortion mechanisms, a number of simulation circuits were constructed and measured with all the standardized and proposed methods. The circuits represent the common basic nonlinearities in audio amplifiers. The details of the measurement methods follow [1], [2], [5].

THD was measured at two different frequencies, 1 kHz and 10 kHz, here termed THD 1 and THD 10, using a signal generator of 0.003% residual harmonic distortion. The harmonic components were measured with a Hewlett-Packard 3581 A spectrum analyzer, and the precent distortion was calculated as an rms sum of the distortion components divided by the amplitude of the fundamental. The sensitivity threshold of this measurement was 0.004%.

SMPTE-IM was measured using two sinusoidal signals having an amplitude ratio of 1:4 and frequencies of 7 kHz

* Presented at the AES 56th Convention, March 1977, Paris; revised July 20, 1977.

and 200 Hz, respectively. The intermodulation sidebands were measured with the spectrum analyzer, and their rms sum was divided by the amplitude of the 7-kHz signal to obtain the percent distortion. The sensitivity threshold of this measurement was 0.02%.

CCIF-IM was measured using two sinusoidal signals of equal amplitude and frequencies of 14.0 kHz and 15.0 kHz. The intermodulation components were measured with the spectrum analyzer, and their rms values were summed. This sum was divided by the rms sum of the amplitudes of the two fundamental signals to obtain the percent distortion. The sensitivity threshold of this measurement was 0.004%.

Noise measurement input signal to the amplifier under test was bandlimited white noise. The input filter attenuation was +48 dB per octave below 11 kHz and −6 dB per octave above 20 kHz. The amplifier output noise signal spectral density was then measured with the spectrum analyzer. The percent distortion was calculated from the ratio of the rms value of the intermodulation noise in the frequency range of 0–9 kHz to the rms value of the noise signal in the frequency range of 11–20 kHz. The sensitivity threshold of this measurement was 0.1% due to the thermal noise in the measuring equipment and in the amplifiers to be measured.

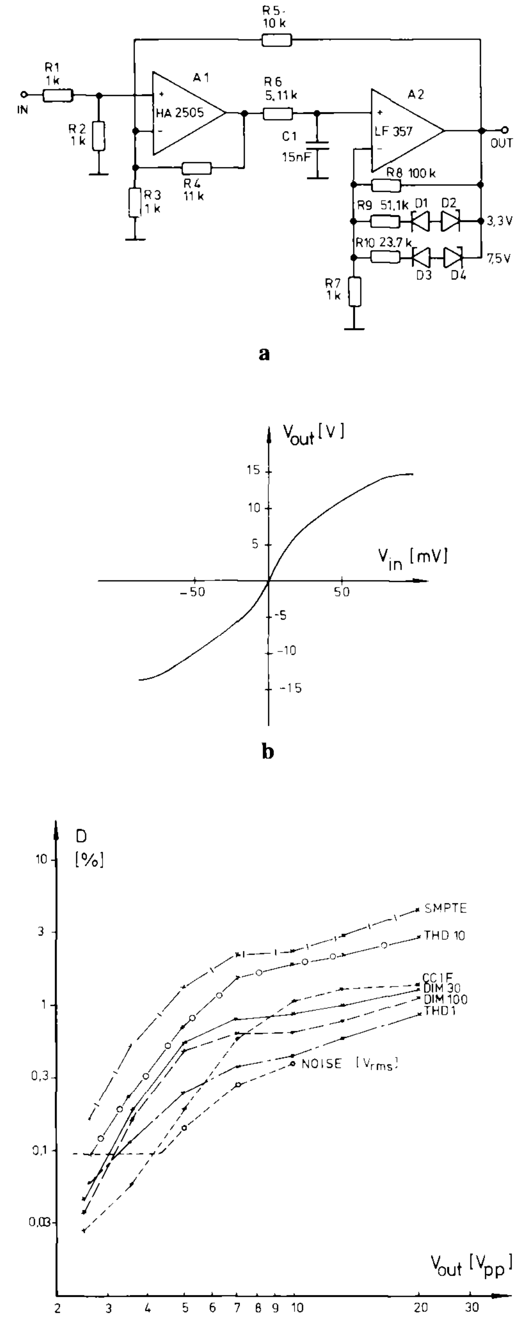
DIM was measured using a sine wave and a square wave of 1:4 peak-to-peak amplitude ratio, and frequencies of 15.0 kHz (f_2) and 3.18 kHz (f_1), respectively. The square wave was low-pass filtered with a −6-dB per octave RC filter having a cutoff frequency of 30 kHz (DIM 30) and 100 kHz (DIM 100) prior to entering the circuit to be measured. The intermodulation components were measured with the spectrum analyzer, and the percent distortion was calculated by summing the rms values of all of type $f_2 \pm nf_1$ intermodulation components in the frequency range of 0–15 kHz, and by dividing this sum by the amplitude of the 15.0-kHz sinusoidal signal. The sensitivity threshold of this measurement was 0.02%.

The circuits which were measured were constructed to simulate typical operating characteristics, signal levels, and frequency behavior of audio circuits which utilize moderate feedback. The open-loop upper cutoff frequency was approximately 2 kHz and the feedback was about 35 dB, values which are common in contemporary power amplifiers. Special attention was paid to ensure that negligible distortion was generated by the basic circuit itself. To facilitate reliable distortion measurements, the artificial open-loop nonlinearities were designed to be about ten times more severe than those commonly found in high-quality audio power amplifiers. The operational amplifiers which were used were tested to have negligible static and dynamic distortion [2].

SYMMETRICAL NONLINEAR OUTPUT STAGE

The circuit used to simulate symmetrical nonlinearities in the output stage is shown in Fig. 1a. A two-stage nonlinearity is caused by Zener diode pairs D_{1-2} and D_{3-4} in the feedback path of A_2. The open-loop (that is, R_5 removed) upper cutoff frequency of the circuit is 2.1 kHz, and the small-signal closed-loop and closed-loop gains are 54.0 dB and 16.3 dB, respectively, corresponding to low-frequency small-signal feedback of 37.7 dB. The measured closed-loop transfer characteristic is so linear that no visible discrepancy from a straight line is discernible before clipping.

The result of each distortion measurement is shown in Fig. 1c. All the measurement methods yield qualitatively and quantitatively the same basic type of response to this



c

Fig. 1. **a.** Simulation circuit of the symmetrically nonlinear output stage. The nonlinearity is generated by D_{1-4} in the feedback path of A_2. **b.** Open-loop transfer characteristic of circuit **a**. The closed-loop transfer characteristic shows no departure from a straight line. **c.** Distortion percentage obtained with different measurement methods. Note that ouput voltage is volts peak-to-peak except for noise measurement, for which it is volts rms. Noise measurement is limited to 0.1%, below which the thermal noise dominates.

nonlinearity. There exists some difference in the sensitivity, SMPTE-IM being the most sensitive and noise measurement the least sensitive. The higher distortion in THD 10 as compared to THD 1 is caused by less feedback being available to correct the distortion at higher frequencies.

It should be noted that the signal levels for the THD, SMPTE-IM, CCIF-IM, and DIM methods are given as peak-to-peak values, in contrast to rms value for the noise method. The noise distortion curve is therefore not directly comparable to the results obtained with other methods. The measuring range of the noise method is limited to 8 V_{rms} maximum because of noise peaks being clipped at the output of A_2 and to 0.1% distortion because of background thermal noise.

ASYMMETRICAL NONLINEAR OUTPUT STAGE

The circuit used is shown in Fig. **2a**. An asymmetry is created by diode D_1 in the feedback path of A_2. The cutoff frequencies and the gains are the same as for the circuit of Fig. **1a**. The open-loop transfer characteristic is shown in Fig. **2b**. The closed-loop transfer characteristic shows no visible departure from a straight line.

The measurement results are shown in Fig. **2c**. The distortion curves are horizontal because the relative nonlinearity remains the same irrespective of signal level. The high sensitivity of the DIM and the SMPTE-IM methods is due to the fact that they basically measure differences in the differential gain, whereas THD and CCIF-IM methods average the effect of nonlinearity on both polarities of the signal.

CROSSOVER DISTORTION IN THE OUTPUT STAGE

The circuit used is shown in Fig. **3a**. Distortion is generated in the unbiased base-emitter junctions of T_1 and T_2. The cutoff frequencies and the gains are the same as for the circuit of Fig. **1a**. The open-loop transfer characteristic is shown in Fig. **3b**. No distortion can be observed in the closed-loop transfer characteristic. The measurement results are shown in Fig. **3c**. A reasonable qualitative and quantitative correlation is obtained, with SMPTE-IM and CCIF-IM being the most sensitive and DIM 100 being the least sensitive. The poor sensitivity of DIM 100 can be explained by noting that due to the steep rise of the squarewave, the signal rests only a very short time in the crossover region. If, however, the square wave is changed to a triangular wave of the same peak-to-peak amplitude, as proposed elsewhere [2], the sensitivity to this type of distortion is greatly enhanced, and the measurement results coincide closely with those obtained with the SMPTE-IM method. The higher sensitivity of the THD 10 is caused by the decrease of feedback at high frequencies due to the limited open-loop bandwidth.

The good sensitivity of the SMPTE-IM and CCIF-IM methods to crossover distortion can be explained by considering the long effective time which the measurement signal of these methods resides in the crossover region. The poor sensitivity of the noise method is caused by the intermodulation noise being mostly generated in the high-frequency end of the spectrum by the crossover distortion mechanism.

"HARD" LIMITING IN THE INPUT STAGE

This situation corresponds to an extreme case of transient intermodulation distortion (TIM) [8]. The circuit used is shown in Fig. **4a**, and the limiting occurs when the peak of the error signal is clipped at the output of A_1. The open-loop upper cutoff frequency is 2.1 kHz, the closed-loop and closed-loop gains are 59.5 dB and 15.3 dB respectively. The low-frequency transfer characteristic, shown in Fig. **4b**, is perfectly linear, as well as the small-signal closed-loop transfer characteristic.

The measurement results are shown in Fig. **4c**. The SMPTE-IM and the THD 1 methods show unmeasurable values of distortion. This is to be expected because they

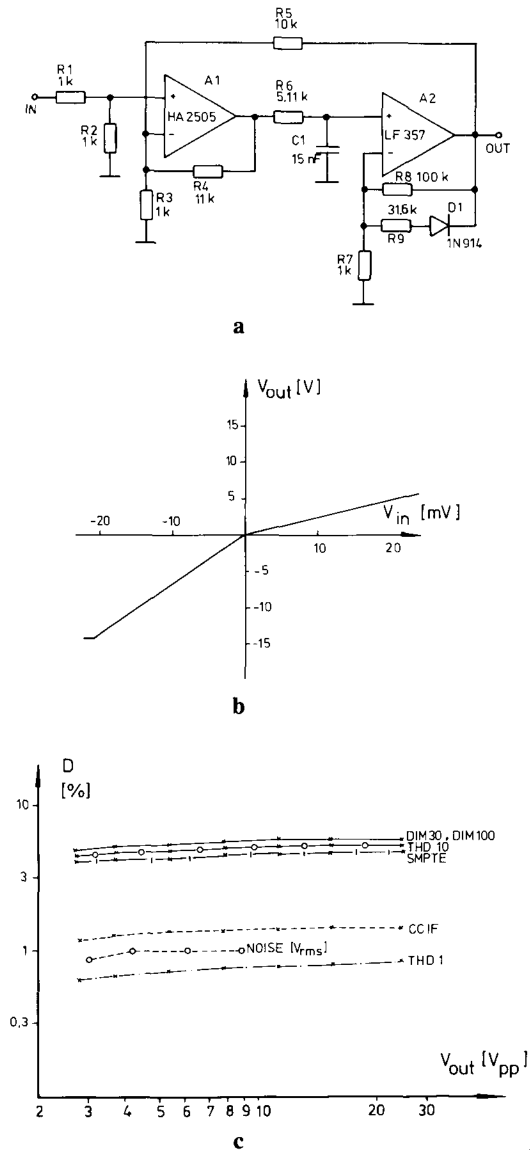


Fig. 2. **a**. Simulation circuit of the asymmetric output stage. The nonlinearity is caused by diode D_1 in the feedback path of A_2. **b**. Open-loop transfer characteristic of circuit **a**. The closed-loop transfer characteristic shows no visible departure from a straight line. **c**. Measurement results for circuit **a**. The noise measurement is limited to 8 V_{rms} maximum due to output clipping in A_2.

basically measure only static distortions [2], [6]. The THD 10 only vaguely indicates the presence of distortion at high output levels, whereas the DIM 30, DIM 100, and noise methods show large values of distortion. In the case of strong dynamic distortion, the noise method has also been reported to correlate well with psychoacoustic judgment [5].

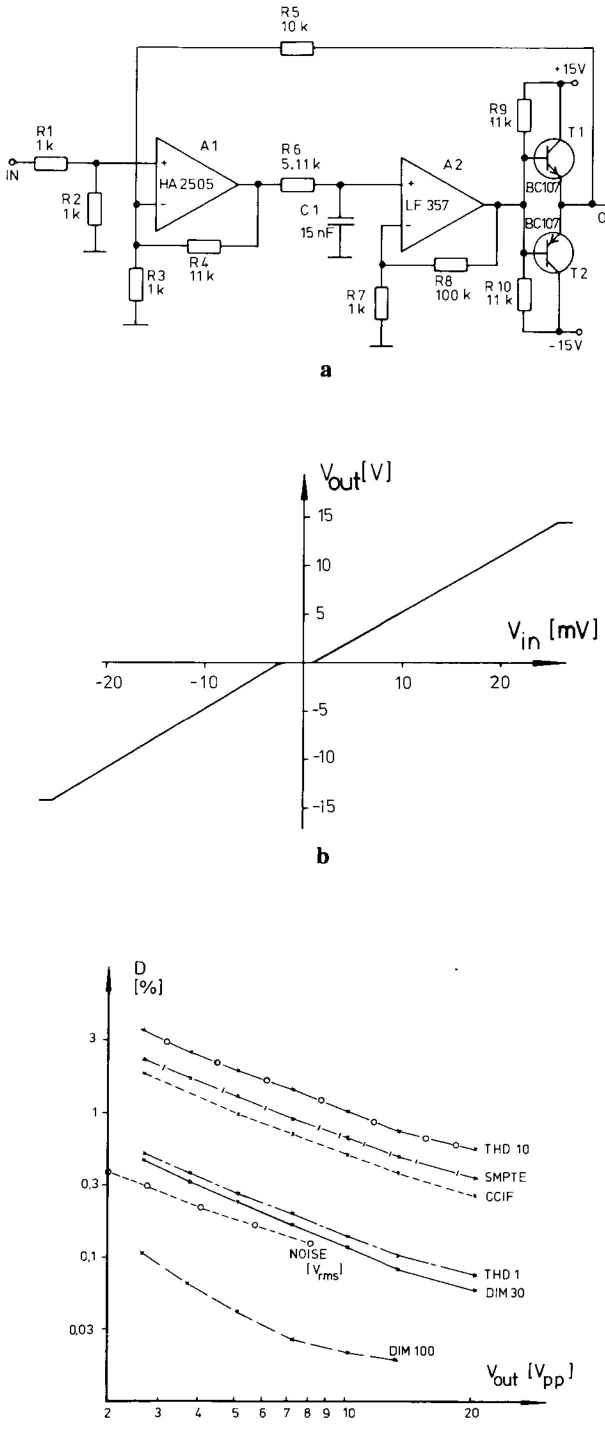


Fig. 3. **a**. Simulation circuit for crossover distortion. The nonlinearity is caused by unbiased base-emitter junctions of T_1 and T_2. **b**. Open-loop transfer characteristic of circuit **a**. The closed-loop transfer characteristic shows no visible departure from a straight line. **c**. Measurement results for circuit **a**. The poor sensitivity of the DIM 100 method is caused by the fact that the signal traverses very rapidly the crossover region.

The poor sensitivity of CCIF-IM is at first surprising. It is caused by the fact that the summation of two high-frequency sinusoids yields a steep rise for only a short period of time, for a small amplitude region, and at a rate of the difference frequency of 1 kHz, whereas in the DIM method the overloading slope, although slightly less steep than the maximum momentary value in the CCIF-IM method, lasts much longer and occurs at a rate of 3.18 kHz.

The characteristic knee in the DIM distortion curves is caused by the very nature of this distortion effect. If the error voltage in the output of A_1 is not large enough to become clipped, the circuit has zero DIM distortion by definition.

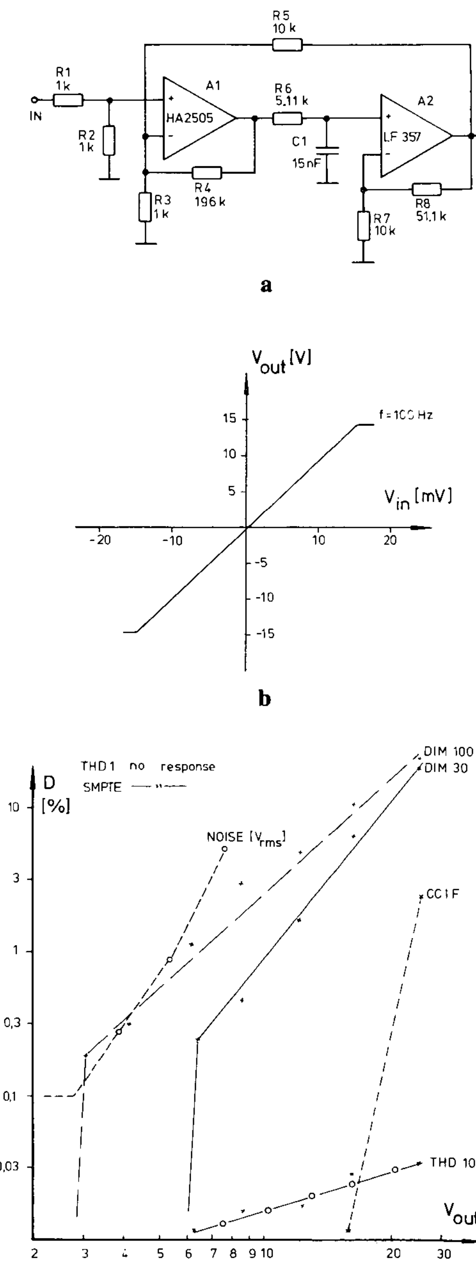


Fig. 4. **a**. Simulation circuit for "hard" TIM. The error voltage is clipped at the output of A_1. **b**. Open-loop transfer characteristic for circuit **a** is perfectly linear. **c**. Measurement results for circuit **a**. THD 1 and SMPTE-IM show no measurable distortion.

SMOOTH NONLINEARITY IN THE INPUT STAGE

The case of a smooth nonlinearity in the input stage corresponds to the general case of TIM [8]. The circuit used is shown in Fig. 5**a**. The open-loop and closed-loop upper cutoff frequencies are 2.1 kHz and 160 kHz, respectively, and the corresponding open-loop and closed-loop low-frequency transfer characteristics are perfectly linear. The measurement results are shown in Fig. 5**c**. As in the preceding case, the SMPTE-IM and THD 1 show unmeasurable distortion whereas DIM, CCIF-IM, and noise measurements react strongly to the distortion. The CCIF-IM is, however, about 10 dB less sensitive than the DIM method for the reasons discussed in the previous section.

SENSITIVITY OF THE METHODS

From the preceding results, Table I of relative sensitivity may be extracted. As can be seen, all the measurement methods have one or more "blind spots" and, consequently, cannot be used alone for a complete specification of the distortion characteristics of an amplifier. The present use of the THD and SMPTE-IM methods in combination is not only redundant but also inadequate, because these methods have common blind spots. Their use as a pair should therefore be discouraged. The rating of THD 1 is poor or zero for all distortion mechanisms, and its use seems, therefore, to be of little value in any case.

In principle, the noise method should offer good possibilities for distortion measurement. The sensitivity for static distortions is, however, poor, and the measurement of dynamic distortions is difficult because of the limitations of output clipping of the noise peaks at high power levels, and thermal noise at low power levels. In its present embodiment it is therefore not well adapted to reliable distortion measurement. More sensitive analogue [4] and digital [7] methods have been proposed, but require complicated instrumentation.

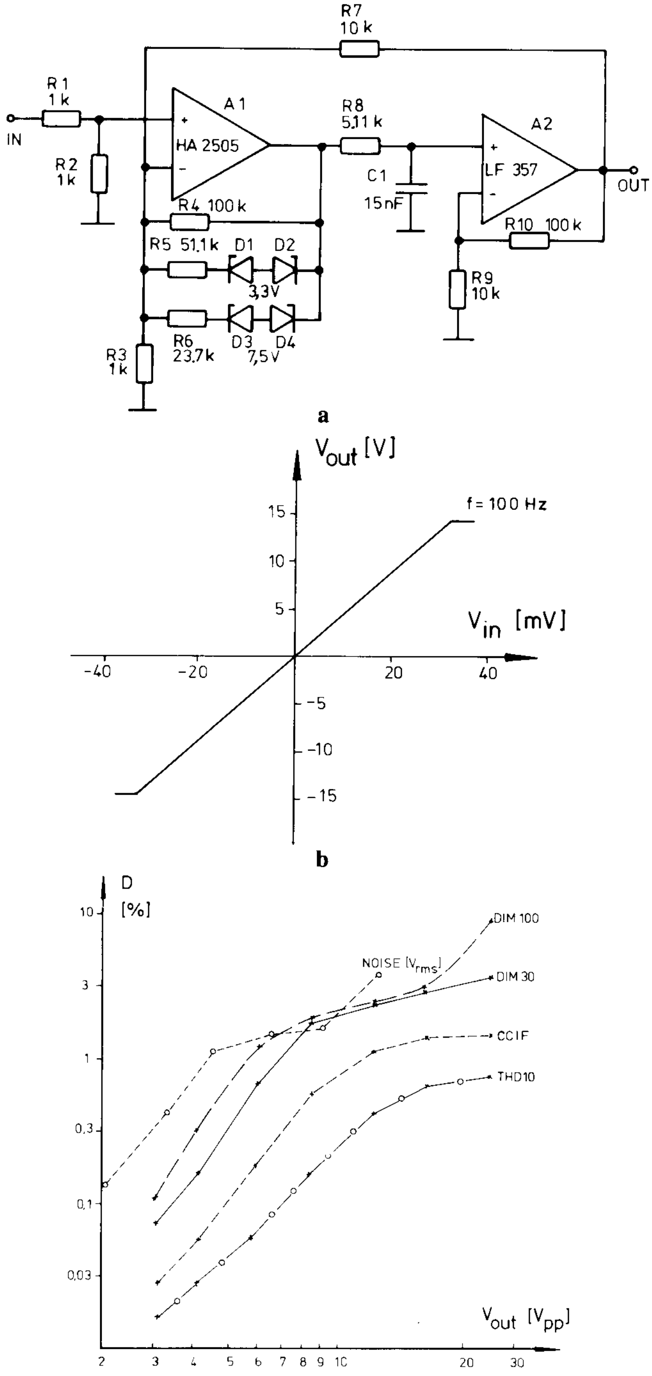
If only one method is to be used, it should be DIM 30, with the option of using triangular wave in addition to sqaure wave [2] to detect static distortions, especially crossover distortion. Optimum method pairs for a complete specification of an amplifier would be either DIM 100 + SMPTE-IM or DIM 100 + CCIF-IM. The latter is preferable because of simplicity of instrumentation. In addition, the THD method could be used to specify amplifier performance below 1 kHz, where only static distortions are likely to have effect.

CORRELATION OF MEASUREMENT RESULTS

A general belief has existed that there is a correlation between the measurement results obtained with different methods, that is, a distortion level of one method can be deduced from a result obtained using another method. To study this, a theoretical amplifier having in equal proportion all the previously described distortion mechanisms was postulated. By using the measurement points of Figs. 1c–5c, the different correlation coefficients r^2 and variance coefficients s_{xy} were computed for relevant method pairs. The coefficients r^2 and s_{xy} were calculated by processing distortion measurement value pairs from method x and method y by linear regression analysis procedure [10]. The coefficients are defined as

$$r^2 = \frac{\left[\Sigma x_i y_i - \frac{\Sigma x_i y_i}{n}\right]^2}{\left[\Sigma x_i^2 - \frac{(\Sigma x_i)^2}{n}\right]\left[\Sigma y_i^2 - \frac{(\Sigma y_i)^2}{n}\right]}$$

$$s_{xy} = \sqrt{\frac{\Sigma (y_i - \hat{y}_i)^2}{n-2}}$$



c

Fig. 5. **a**. Simulation circuit for TIM. The error voltage is suppressed by $D_1 - D_4$ in the feedback path of A_1. **b**. Open-loop transfer characteristic of circuit **a** is perfectly linear. **c** Measurement results for circuit **a**. THD 1 and SMPTE show no measurable distortion.

Table 1. Sensitivity of different distortion measurement methods.

Distortion Mechanism	Measurement Method				
	THD*	SMPTE	CCIF	DIM	NOISE†
Symmetrical Output Nonlinearity	Poor (1) Good (10)	Excellent	Good	Moderate	Poor
Asymmetrical Output Nonlinearity	Poor (1) Good (10)	Excellent	Poor	Excellent	Poor
Crossover Distortion	Poor (1) Excellent (10)	Excellent	Excellent	Poor‡	Poor
Hard Input—Stage Limiting	Zero	Zero	Poor	Excellent	Excellent
Smooth Input—Stage Limiting	Zero (1) Poor (10)	Zero	Good	Excellent	Excellent

* Numbers in parentheses denote THD 1 and THD 10.
† Applicable only up to output level of 10 dB below clipping.
‡ May be changed to "excellent" by replacing square wave with triangular wave as proposed in [2].

where x_i and y_i are values from method x and method y. $\hat{y}_i$ is the estimated value of y_i by the regression procedure, n is the number of points, and i is a positive integer denoting the running number of the measurement.

The coefficient r^2 gives the correlation between method x and method y; the closer r^2 is to 1 the better the correlation. If $r^2 \geq 0{,}6$, there is a strong dependence between the results obtained with the two methods. The variance coefficient s_{xy} shows the scattering of the results. The smaller s_{xy}, the smaller the scattering and the better the correlation. The results are shown in Fig. 6, and the following conclusions may be drawn.

1) If only static distortions are considered, a reasonable correlation exists between SMPTE-IM, THD 1, THD 10, and DIM 30. The correlation between SMPTE-IM and CCIF-IM is not particularly good.

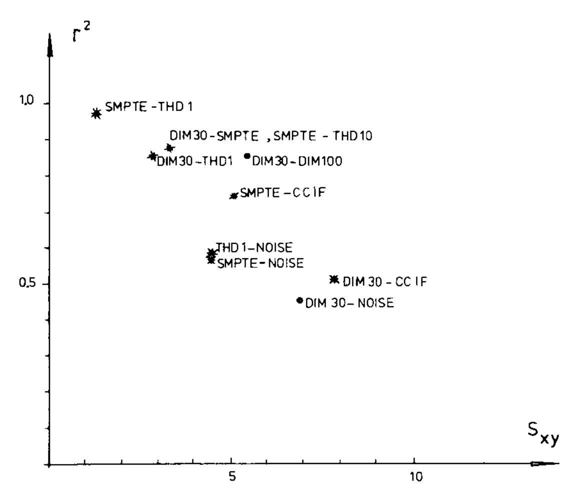


Fig. 6. Correlation coefficients for results obtained with different measurement method pairs. The asterisks stand for static distortions only, the dots for all the distortion mechanisms. For other combinations than those shown, no correlations do exist. DIM 30–CCIF correlation includes all nonlinearities except hard TIM.

2) If both static and dynamic distortions are considered, the only reasonable correlation exists between DIM 30 and DIM 100. All the other methods have a poor or nonexistent correlation with each other.

It is therefore evident that in the general case no fixed relationships exist between the results obtained with different methods.

COMMERCIAL POWER AMPLIFIERS AND OPERATIONAL AMPLIFIERS

In order to study real-life mixed distortion mechanisms, a total of 22 high-quality power amplifiers and operational amplifiers were measured. The 11 power amplifiers were Sony TA-8650, Yamaha CR-600, Quad 405, JVC JR-5300, Tandberg TR 2025, Kenwood KR-4600, Luxor 8100, Acoustolab Disco, ASA 4000, Pioneer SX-650, and Marantz 1200 B. The measurements were performed under normal conditions, loudness control disabled, tone controls in midposition, and with specified resistive output load.

Figs. 7–9 represent the distortion measurement results of three typical and representative cases of all the 11 power amplifiers tested. The amplifier of Fig. 7 shows close identity to a mixed case of asymmetrical output stage (Fig. 2c) and hard TIM (Fig. 4c). The amplifier in Fig. 8 shows a mixed case of symmetrical and asymmetrical output stage. However, the form of the curves indicates some anomalous behavior which may point toward more complicated distortion mechanisms. The amplifier of Fig. 9 shows strange distortion behavior, as the difference between the SMPTE-IM and THD measurement results would necessitate some kind of cancellation effects taking place. Furthermore, the dramatic increase of noise distortion at high power levels, being incompatible with no increase in DIM, points to a complex time-dependent distortion mechanism.

The operational amplifiers which were tested were μA 709, μA 739, μA 741, MC 1450, RS 536, LM 301, LM

318, HA 2505, LF 356, LF 357, and CA 3180. The operating conditions were as follows: noninverting circuit, 20 dB gain setting, recommended compensation, ± 15-V operating voltages, and 5-kΩ resistive load. The measurement procedures were basically the same as reported in detail elsewhere [2], and typical results were extremely small static distortions and high or very high dynamic distortion.

To study the correlation of the results obtained with different measurement methods, the data points for the power amplifiers were used in straightforward correlation computation. The results are shown in Fig. 10 with an asterisk. All the correlation coefficients are about 0.5 or below with a high variance, showing that no reliable correlation exists. When the data points from the measurements with the operational amplifiers were added, the total correlation coefficients, marked with a dot in Fig. 10, changed dramatically. In essence, those correlations which included a method sensitive for static distortion, such as SMPTE-IM or THD 1, and a method sensitive for dynamic distortion, such as DIM, decreased to zero. An increase was noted in those correlation coefficients which included a method pair sensitive to the same kind of distortion.

CONCLUSIONS

By the use of experimental measurements on five basic distortion mechanisms, it has been shown that

1) The standardized and proposed distortion measurement methods react very differently to different distortion mechanisms

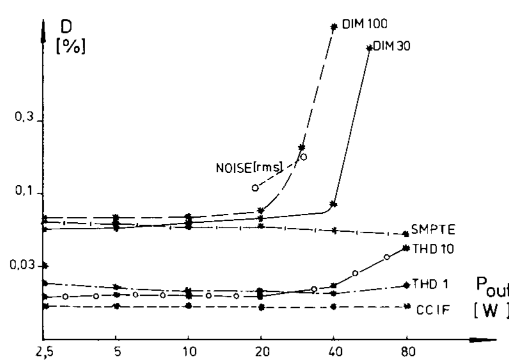


Fig. 7. Distortion data for a power amplifier having predominantly dynamic distortions. Distortion behavior is normal.

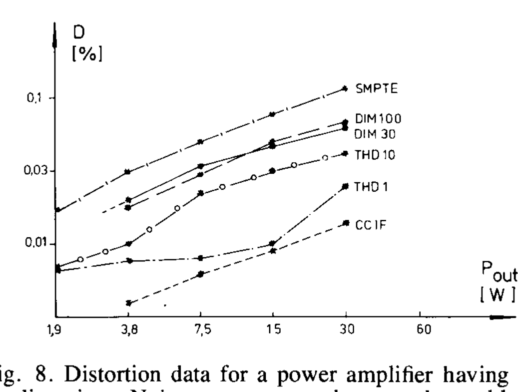


Fig. 8. Distortion data for a power amplifier having mostly static distortions. Noise measurement shows no detectable distortion. The DIM 30–DIM 100 and the THD 1–THD 10 curves show anomalous distortion behavior.

2) there exists no reliable correlation between the results obtained with any two of the methods

3) The use of the total harmonic distortion measurement and the SMPTE intermodulation measurement is redundant

4) THD and SMPTE-IM methods do not react to dynamic distortion mechanisms

5) the CCIF intermodulation method does not reliably indicate the presence of "hard-limiting" transient intermodulation distortion

6) the DIM measuring method does not reliably indicate crossover distortion, unless the square-wave component is changed to a triangular wave

7) the noise method is difficult to use because of limitations imposed by thermal noise and output clipping

8) optimum measurement methods for reliable distortion specification of audio amplifiers are the DIM 30 method used with square/triangular option, or the DIM 100 method used in conjunction with the CCIF-IM method.

In view of the fact that dynamic distortions seem to be the prominent distortion phenomena in the amplifiers tested in this study, as well as in earlier investigations [2],

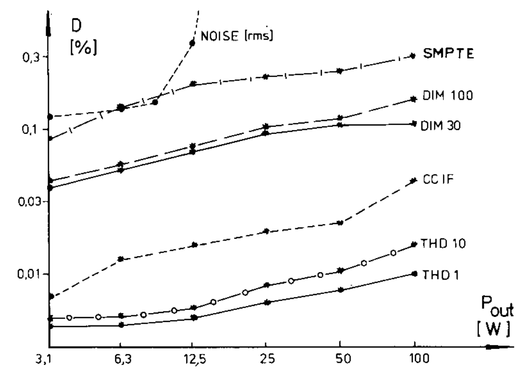


Fig. 9. Distortion data for a power amplifier having complex distortion behavior. The dramatic increase of noise distortion without corresponding increase in DIM points toward a time-dependent distortion mechanism. The grouping of the THD curves with respect to the others shows a tendency to some kind of distortion cancellation effect.

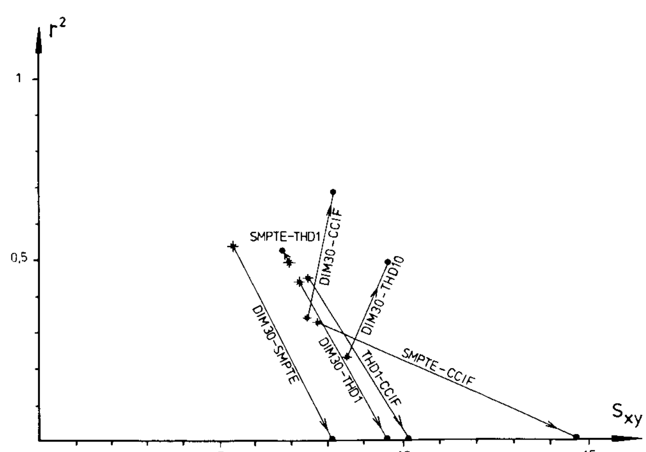


Fig. 10. Correlation coefficients for power amplifier distortion measurements are marked with an asterisk. When the distortion data of operational amplifiers are included, the correlation coefficients are changed to those marked with dots.

[9], the use of an appropriate measurement method would be desirable. Because audio signals do contain transients which resemble the rise of the DIM measurement signal, and because it has been shown that these may cause severe intermodulation which remains undetected with other methods, there would seem to be a strong case for recommending the general use of the DIM method.

REFERENCES

[1] "Sound System Amplifiers," International Electrotechnical Commision, Publ. IEC 268-3 (1969).

[2] E. Leinonen, M. Otala, and J. Curl, "A Method for Measuring Transient Intermodulation Distortion (TIM)," *Audio Eng. Soc.*, vol. 25, pp. 170-177 (Apr. 1977).

[3] C. Schrock, "The Tektronix Cookbook of Standard Audio Tests," Tektronix, Inc., 1975, pp. 17-18.

[4] R. A. Belcher, "Test Noise Signals for Use in the Measurement of Non-linear Distortion, B.B. C. Research Dept., London, Rep. 1974/2, pp. 195-196, 1974.

[5] F. M. Huges, "Seventeen Amplifiers," *HiFi for Pleasure*, pp. 56-63 (Mar. 1976).

[6] M. Otala, "Non-linear Distortion in Audio Amplifiers," *Wireless World*, vol. 83, no 1, pp. 41-43 (1977).

[7] M. Otala and E. Leinonen, "Possible Methods for the measurement of Transient Intermodulation Distortion," presented at the 53rd Convention of the Audio Engineering Society, Zürich, Switzerland, March 1976. Available here Technical Research Centre of Finland, Electrical and Nuclear Technology Ser. Rep. 16, 16 pp., 1976.

[8] M. Otala and E. Leinonen, "The theory of Transient Intermodulation Distortion," *Monitor-Proc. IREE*, vol. 37, no 5, pp. 53-59 (1976), also, *IEE Trans. Acoustics, Speech and Signal Processing*, vol. ASSP-25, pp. 2-8 (1977).

[9] M. Otala and R. Ensomaa, "Transient Intermodulation Distortion in Commercial Audio Amplifiers," *J. Audio Eng. Soc*, *(Project Notes)*, pp. 244-246 (May 1974).

[10] N. R. Draper, and H. Smith, *Applied Regression Analysis*, (Wiley, New York, 1966), pp. 7-35.

The biographies of Eero Leinonen and Matti Otala appeared in the April 1977 issue.