

CORRELATION OF AUDIO DISTORTION SPECIFICATIONS

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CORRELATION OF AUDIO DISTORTION SPECIFICATIONS

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ABSTRACT

The sensitivity of five audio distortion measurement methods has been investigated with experimental measurements of circuits simulating basic archetypal distortion mechanisms. The results show that the ordinary measurement methods, THD and SMPTE-IM, do not reveal dynamic distortions, and that every method has unacceptably low sensitivity for at least one distortion mechanism. The combined use of the DIM method and the CCIF-IM method for a complete specification of amplifier distortion is recommended, because their "blind spots" do not overlap.

Distortion measurements of eleven commercial power amplifiers and eleven operational amplifiers show a mixture of the archetypal 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 with the different methods have been found to correlate qualitatively but not quantitatively for each type of nonlinearity separately. In a mixed case and for commercial amplifiers the qualitative correlation disappears, and there seems to be no reliable way of predicting the measurement result of one method from that of another method in the case of an unknown amplifier.

INTRODUCTION

Distortion in audio equipment is presently measured and specified with 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], originally intended for carrier-frequency telephony measurements, the noise transfer method [3,4] and the dynamic intermodulation measuring method (DIM) [2]. It has also 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 are dependent also on the time properties of the signal to be reproduced, and not on its amplitude characteristics alone, as is the case with static distortions, for example harmonic distortion [5].

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 sensitivities of the different measurement methods on different stereotypic distortion mechanisms, a number of simulation circuits were constructed and measured with all the standardized and proposed methods. The circuits represent the common archetypal nonlinearities in audio amplifiers. The details of the measurement methods were as follows [1,2,4]:

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 % background harmonic distortion. The harmonic components were measured using a HP 3581 A spectrum analyzer and the distortion was calculated by rms summing of the components and by dividing this sum by the amplitude of the fundamental.

SMPTE-IM was measured using two sinusoidal signals having an amplitude ratio of 1:4 and frequencies of 7 kHz and 200 Hz, respectively. The intermodulation sidebands were measured with the HP 3581 A spectrum analyzer, rms summed and divided by the amplitude of the 7 kHz signal.

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 HP 3581 A spectrum analyzer and rms summed. This sum was divided by the rms sum of the amplitudes of the two fundamental signals.

NOISE MEASUREMENT input signal to the amplifier under test was band-limited white noise. The input filter attenuation was +48 dB/octave below 11 kHz and -6 dB/octave above 20 kHz. The amplifier output noise signal spectral density was measured using the HP 3581 A spectrum analyzer, and the 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.

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 and 3,18 kHz, respectively. The square wave was low-pass filtered with a -6 dB/octave RC filter having a cut-off frequency of 30 kHz (DIM30) and 100 kHz (DIM100) prior to entering the circuit to be measured. The intermodulation components were measured with the HP 3581 A spectrum analyzer and the distortion was calculated by rms summing of all intermodulation components and by dividing this sum by the amplitude of the 15,0 kHz sinusoidal signal.

The circuits to be measured were constructed to resemble typical operating characteristics, signal levels and frequency behaviour of audio circuits of moderate feedback. The open-loop upper cut-off frequency was around 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 one decade more severe than those commonly found in high-quality audio power amplifiers.

SYMMETRICAL NONLINEAR OUTPUT STAGE

The circuit used 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 (i.e. R_5 removed) upper cut-off frequency of the circuit was 2,1 kHz and the small-signal closed-loop upper cut-off frequency was 130 kHz. The small-signal open-loop and closed-loop gains were 54,0 dB and 16,3 dB, respectively, corresponding to low-frequency small-signal feedback of 37,7 dB. The open-loop transfer function is shown in Fig. 1b. The closed-loop transfer function is so linear that no visible discrepancy from a straight line is discernible before clipping.

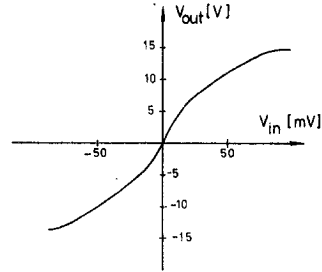
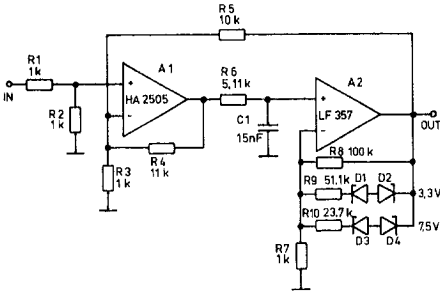


Fig. 1a. The simulation circuit of the symmetrically nonlinear output stage. The nonlinearity is generated by D_{1-4} in the feedback path of A_2 .

Fig. 1b. The open-loop transfer function of the circuit of Fig. 1a. The closed-loop transfer function shows no departure from a straight line.

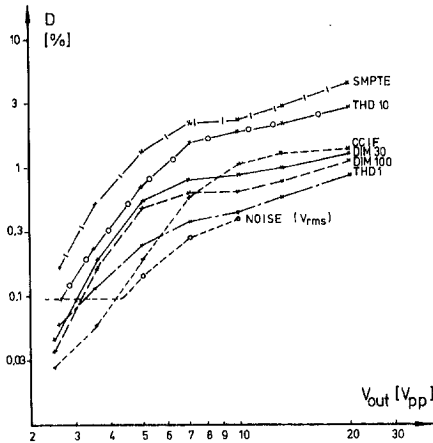


Fig. 1c. The distortion percentage obtained with different measurement methods. Note that output voltage is volts peak-to-peak except for noise measurement for which it is volts rms. Noise measurement is limited to 0,1 %, below which the thermal noise dominates.

The results are shown in Fig. 1c. All the measurement methods yield qualitatively and quantitatively the same basic type of response to this 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 were the same as for the circuit of Fig. 1a. The open-loop transfer function is shown in Fig. 2b, and the closed-loop transfer function shows no visible departure from a straight line.

The measurement results are shown in Fig. 2c. The distortion curves run 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.

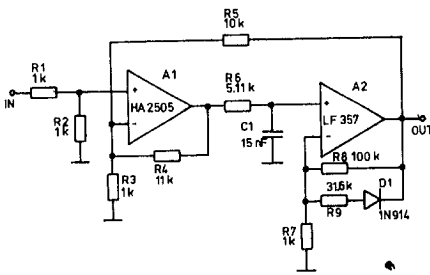


Fig. 2a. The simulation circuit of the asymmetric output stage. The nonlinearity is caused by diode D_1 in the feedback path of A_2 .

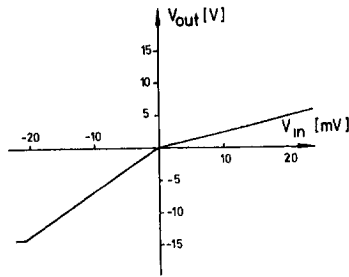


Fig. 2b. The open-loop transfer function of the circuit of Fig. 2a. The closed-loop transfer function shows no visible departure from a straight line.

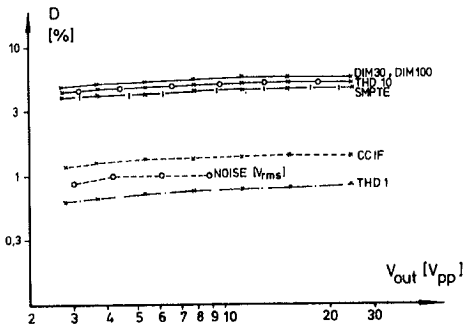


Fig. 2c. The measurement results for the circuit of Fig. 2a. The noise measurement is limited to $8 V_{rms}$ maximum due to output clipping in A_2 .

CROSS-OVER DISTORTION IN THE OUTPUT STAGE

The circuit used is shown in Fig. 3a. The cutoff frequencies and the gains were the same as for the circuit of Fig. 1a. Then open-loop transfer function is shown in Fig. 3b and no distortion can be noted in the closed-loop transfer function. The distortion is generated in the unbiased base-emitter junctions of T_1 and T_2 . 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 DIM100 being the least sensitive. The poor sensitivity of DIM100 can be explained by noting that due to the steep rise of the square-wave, the signal rests only a very short time in the cross-over 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 THD10 is caused by the decrease of feedback at high frequencies due to the open-loop pole.

The good sensitivity of the SMPTE-IM and the CCIF-IM methods to the cross-over distortion can be explained by considering the long effective time which the measurement signal of these methods resides in the cross-over 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.

"HARD" LIMITING IN THE DRIVER STAGE

This situation corresponds to an extreme case of transient intermodulation distortion (TIM) [7]. 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 was 2.1 kHz, the closed-loop upper cutoff frequency was 330 kHz, and the open-loop and closed-loop gains were 59.5 dB and 15.3 dB, respectively. The low-frequency transfer function, shown in Fig. 4b, is perfectly linear, as well as the small-signal closed-loop transfer function.

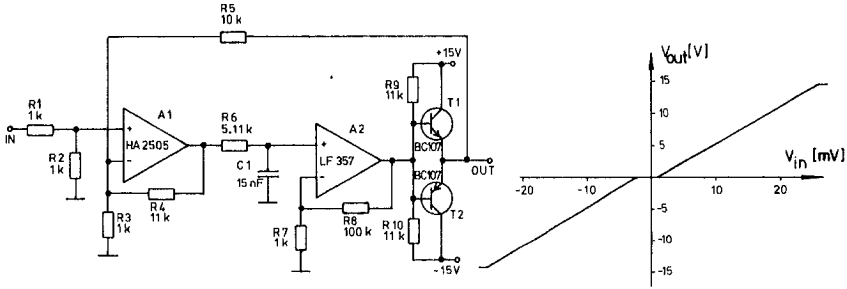


Fig. 3a. The simulation circuit for cross-over distortion. The nonlinearity is caused by unbiased base-emitter junctions of T_1 and T_2 .

Fig. 3b. The open-loop transfer function of the circuit of Fig. 3a. The closed-loop transfer function shows no visible departure from a straight line.

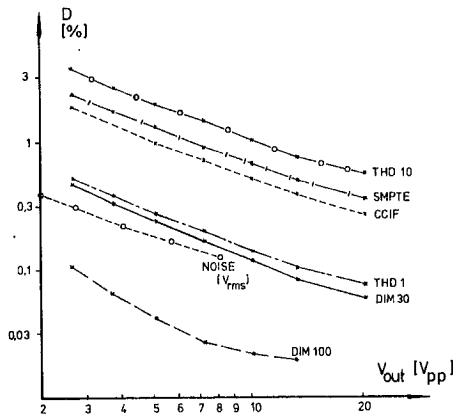


Fig. 3c. The measurement results for the circuit of Fig. 3a. The poor sensitivity of the DIM100 method is caused by the fact that the signal traverses very rapidly the cross-over region.

The measurement results are shown in Fig. 4c. The SMPTE-IM and the THD1 methods show unmeasurable values of distortion, which is to be expected as they basically only measure static distortions [2,5]. The THD10 only vaguely indicates the presence of distortion at high output levels, whereas the DIM30, DIM100 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 [4].

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

GRADUAL NONLINEARITY IN THE DRIVER STAGE

This situation corresponds to the general case of TIM [7]. The circuit used is shown in Fig. 5a. The open-loop and closed-loop upper cutoff frequencies were 2,1 kHz and 160 kHz, respectively, and the open-loop and closed-loop low-frequency gains were 54,0 dB and 15,5 dB. The open-loop and closed-loop low-frequency transfer functions are perfectly linear. The measurement results are shown in Fig. 5c. Again, SMPTE-IM and THD1 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 those reasons discussed in the previous section.

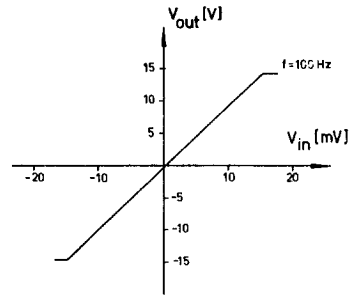
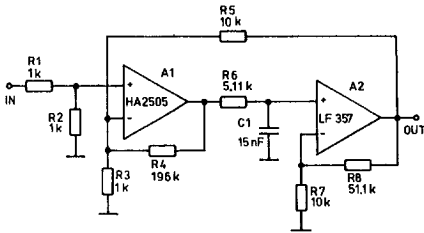


Fig. 4a. The simulation circuit for "hard" TIM. The error voltage is clipped at the output of A_1 .

Fig. 4b. The open-loop transfer function of the circuit of Fig. 4a. is perfectly linear.

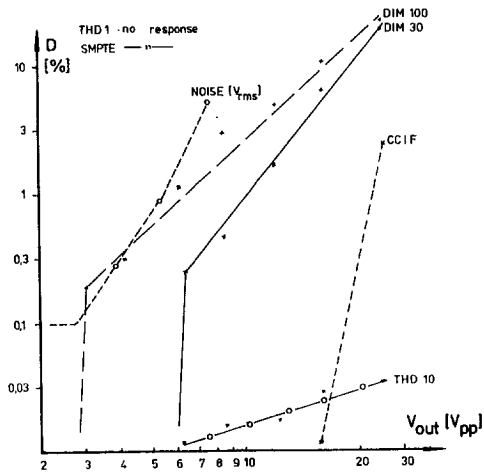


Fig. 4c. Measurement results for the circuit of Fig. 4a. THD1 and SMPTE-IM show no measurable distortion.

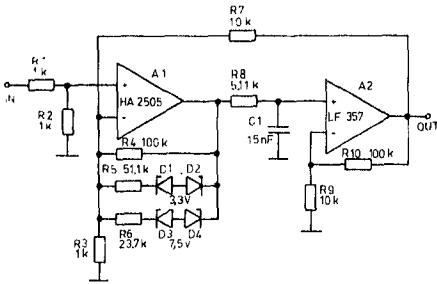


Fig. 5a. The simulation circuit for "soft" TIM. The error voltage is suppressed by $D_1 - D_4$ in the feedback path of A_1 .

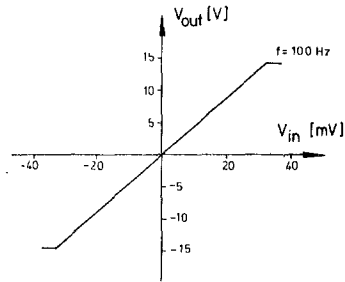


Fig. 5b. The open-loop transfer function of the circuit of Fig. 5a. is perfectly linear.

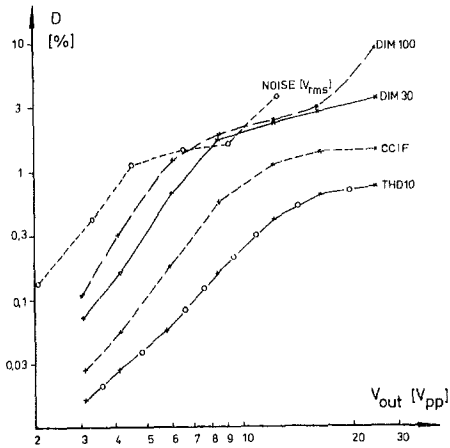


Fig. 5c. Measurement results for the circuit of Fig. 5a. THD1 and SMPTE show no measurable distortion.

SENSITIVITY OF THE METHODS

From the above results, Table 1 of relative sensitivity may be extracted.

DISTORTION MECHANISM	MEASUREMENT METHOD				
	THD	SMPTE	CCIF	DIM	NOISE
SYMMETRICAL OUTPUT	poor (1) good (10)	excellent	good	moderate	poor
ASYMMETRICAL OUTPUT	poor (1) good (10)	excellent	poor	excellent	poor
CROSS-OVER	poor (1) excellent (10)	excellent	excellent	poor ^{a)}	poor
HARD DRIVER	zero	zero	poor	excellent	excellent
GRADUAL DRIVER	zero (1) poor (10)	zero	good	excellent	excellent

Table 1. Sensitivity of different distortion measurement methods.

a) May be changed to "excellent" by replacing square wave with triangular wave as proposed in [2].

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 parallel is not simply redundant but also inadequate, because both methods have common blind spots. Their use as a pair should therefore be discouraged. The rating of THD1 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 is difficult because of thermal noise limiting the sensitivity in the low end, and output clipping at the high end. In its present embodiment it is therefore not well adapted to reliable distortion measurement. More sensitive analogue [3] and digital [6] methods have been proposed, but require expensive and complicated instrumentation.

If only one method is to be used, it should be DIM30, with the option of using triangular wave in addition to square wave [2] to detect static distortions, especially cross-over distortion. Optimum method pairs for a complete specification of an amplifier would be either DIM100 + SMPTE-IM or DIM100 + CCIF-IM. The latter is preferred because of simplicity of instrumentation. In addition, the THD method could be used to specify amplifier low-frequency performance below 1 kHz, where only static distortions are likely.

CORRELATION OF MEASUREMENT RESULTS

A general belief has existed that there is a correlation between the measurement results obtained with different methods, i.e. 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

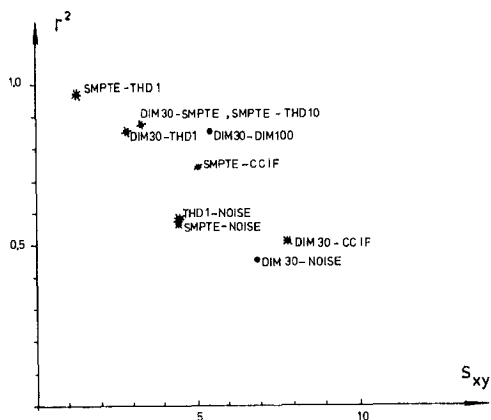


Fig. 6. Correlation coefficients for results obtained with different measurement method pairs. The asterisks stand for static distortions only, the dots for all the distortion mechanisms. For other combinations than those shown, no correlations do exist. DIM30-CCIF correlation includes all nonlinearities except hard TIM.

points of Figs. 1c-5c, the different correlation coefficients r^2 and variance coefficients s_{xy} were computed for relevant method pairs. The results are shown in Fig. 6, and the following conclusions may be drawn:

- if only static distortions are considered, a reasonable correlation exists between SMPTE-IM, THD1, THD10 and DIM30. The correlation between SMPTE-IM and CCIF-IM is not particularly good.
- if both static and dynamic distortions are considered, the only reasonable correlation exists between DIM30 and DIM100. 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 do exist between the results obtained with different methods.

COMMERCIAL AMPLIFIERS

In order to study real-life mixed distortion mechanisms, 22 high-quality power amplifiers and operational amplifiers were measured. The 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 in nominal conditions, loudness control disabled, tone controls in midposition, and with specified resistive output load.

Figs. 7, 8 and 9 represent typical results with different measurement methods. 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 behaviour which may point towards more complicated distortion mechanisms.

The amplifier of Fig. 9 shows strange distortion behaviour, 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 at high power levels, being incompatible with no increase in DIM, points to a complex time-dependent distortion mechanism

The operational amplifiers 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: Non-inverting circuit, 20 dB gain setting, recommended compensation, ± 15 V operating voltages, and 5 k Ω 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 TIM distortion.

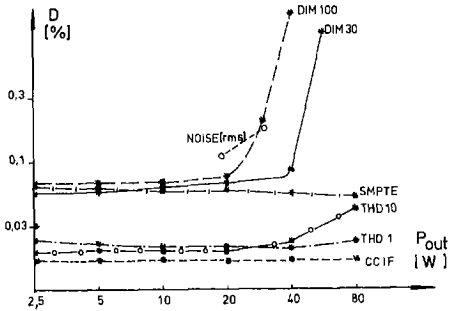


Fig. 7. The distortion data for a power amplifier having predominantly dynamic distortions. Distortion behaviour is normal.

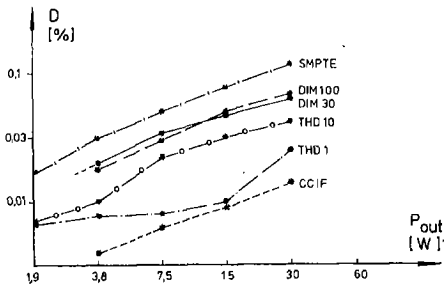


Fig. 8. The distortion data for a power amplifier having mostly static distortions. Noise measurement shows no detectable distortion. The DIM30 - DIM100 and the THD1 - THD10 curves show anomalous distortion behaviour.

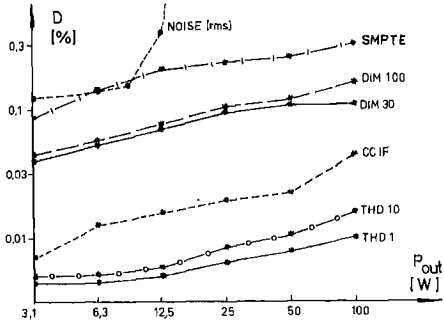


Fig. 9. The distortion data for a power amplifier having complex distortion behaviour. The dramatic increase of noise without corresponding increase in DIM points towards a time-dependent distortion mechanism. The group in of the THD curves with respect to the others show a tendency to some kind of distortion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

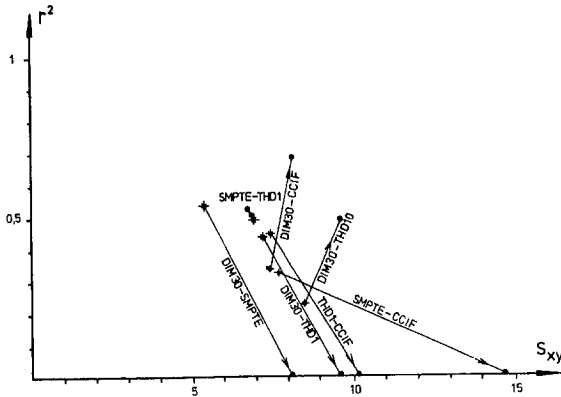


Fig. 10. Correlation coefficients for power amplifier distortion measurements are marked with an asterisk. When the distortion data of operational amplifiers is included, the correlation coefficients are changed to those marked with dots.

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, e.g. SMPTE-IM or THD1, and a method sensitive for dynamic distortion, e.g. DIM, decreased to zero. Increase was noted in those correlation

coefficients which included a method pair sensitive to the same kind of distortion.

CONCLUSIONS

Using experimental measurements on five archetypal distortion mechanisms, it has been shown that

- the standardized and proposed distortion measurement methods react very differently to different distortion mechanisms
- there exists no reliable correlation between the results obtained with any two of the methods
- the use of the total harmonic distortion measurement and the SMPTE intermodulation measurement is redundant
- THD and SMPTE-IM methods do not react to dynamic distortion mechanisms
- the CCIF intermodulation method does not reliably indicate the presence of "hard-limiting" transient intermodulation distortion
- the DIM measuring method does not reliably indicate cross-over distortion, unless the square-wave component is changed to a triangular wave
- the noise method is difficult to use due to limitations imposed by thermal noise and output clipping
- optimum measurement methods for reliable distortion specification of audio amplifiers are the DIM30 method used with square/triangular option, or the DIM100 method used in conjunction with the CCIF-IM method.

In view of the fact that the dynamic distortions seem to be prominent distortion phenomena in the amplifiers in this study, as well as in earlier investigations [2,8], the use of an appropriate measurement method would be desirable. As audio signals do contain transients which resemble the rise of the

DIM measurement signal, and as 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.

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