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SLEWING INDUCED DISTORTION AND IT'S EFFECT ON AUDIO AMPLIFIER PERFORMANCE--WITH CORRELATED MEASUREMENT/LISTENING RESULTS

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Abstract

There has been a great deal of material in the literature in recent years on transient intermodulation distortion (TIM) as a major distortion mechanism in audio amplifiers, particularly IC op amps. A detailed study of high level high frequency performance of op amps involving over 100 different device samples reveals the true distortion mechanism to be slew induced distortion (SID), with TIM actually being only one particular manifestation of SID.

The study demonstrates a direct correlation between device slewing rate and THD, two tone IM, and TIM test results, as well as listening tests. The results allow not only predictable electrical and audible results of feedback amplifiers based on slew rate behaviour, but also dispel several popular myths involving open loop bandwidth and feedback factors as design criteria.

Some major implications of this study are a new slew rate criteria for high quality audio circuit performance, the nature of various op amp slewing behaviour patterns, the audible nature of SID as correlated to actual slew rate, and the necessity for industry recognition of slew rate in both equipment specs and testing methods.

Introduction

The frequent lack of correlation between an amplifier's measured versus listening performance is well known. This leads to the immediate conclusion that relevant measurements are not being performed. Transient Intermodulation Distortion (TIM) [3,4,27] has been advanced as a distortion mechanism which could be partially responsible for this lack of correlation, and yet elude common measurements.

Most work on TIM has dealt with clipping of an amplifier's internal stages, which produces gross slew limiting on the amplifier output. Of much greater interest is the performance of an amplifier properly operated below its slew limit, and that is what most of this paper is concerned with. It will be shown that Slew Induced Distortion (SID) is the major distortion mechanism in most present day amplifiers. Measurements of this distortion will be presented and compared with calculations of its magnitude. It will be shown that an amplifier's Slew Rate (SR) and Gain Bandwidth product (GxBW or (ωu)) are its most important specifications for audio performance. Some design quidelines will be given to allow designers to use and design amplifiers to avoid this type of distortion.

Data from three types of distortion tests will be presented. These are Total Harmonic Distortion (THD), Two Tone Difference Inter-Modulation Distortion (IM), and the recently proposed test for TIM.[16] Some of the relative merits of these measurement techniques will be discussed and it will be shown that, where applicable, THD is the optimum technique. It will become obvious that low frequency distortion tests such as 1 khz THD or 60 hz, 7 khz IM tests are useless for detecting SID. It will also become obvious that I.C. op amps, viewed with suspicion by some, are capable of superlative performance when properly operated below Slew Rate.

The Slew Induced Distortion Mechanism

It is important to understand the dominant distortion mechanism of an amplifier. We will mostly deal with operational amplifier circuits, but since most present day power amps are of similar design the discussion and data will be relevant to them as well.

Fig. 1a is an idealized model of our basic amplifier. Its input stage is a voltage to current converter or transconductance stage, characterized by the parameter g_m. The output current of this stage is simply

$$\Delta i = g_m \Delta V \qquad (1)$$

The second stage of our amplifier is an integrator with an output voltage

$$V_o = \frac{1}{C}\int \Delta i dt = \frac{g_m}{C}\int \Delta V\, dt \qquad (2)$$

The resistor R is responsible for the finite D.C. gain of the amplifier. At low frequencies the open loop gain is

$$A_o = g_m R \qquad (3)$$

The open loop frequency response begins dropping (Fig. 1b) at a frequency

$$\omega_o = \frac{1}{RC} \qquad (4)$$

Since for audio circuits we have no interest in the amplifier gain at D.C., it is much more convenient to neglect R (as in equation 2) and work with the unity gain bandwidth which, due to the integrator's -6dB / octave response is equal to the gain bandwidth product.

$$\omega_u = A(\omega) \times \omega = A_o\omega_o = g_m R \times \frac{1}{RC} = \frac{g_m}{C} \qquad (5)$$

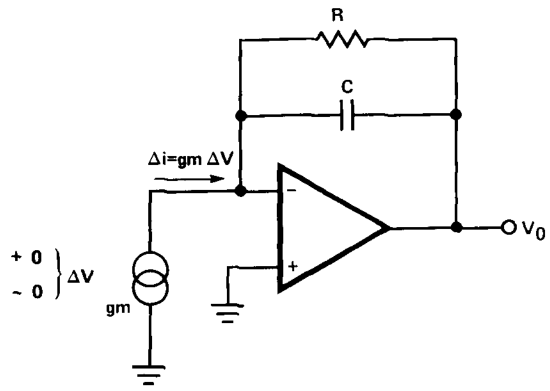


FIGURE 1a AMPLIFIER MODEL

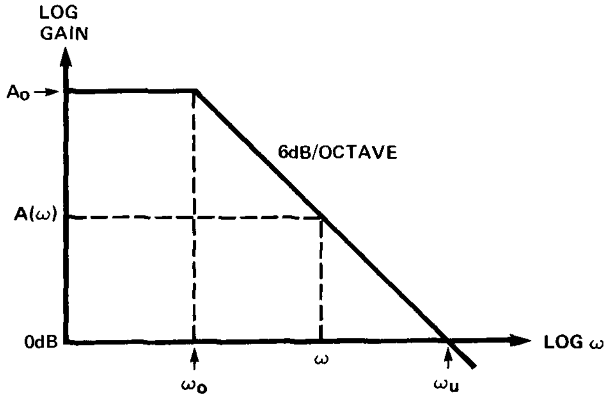


FIGURE 1b FREQUENCY RESPONSE

Refering to equation 2, we have

$$Vo = \omega u \int \Delta V \, dt \qquad (6)$$

Thus for an amplifier with a 6 dB /octave frequency response, the amplifier can be characterized simply by its unity gain bandwidth or gain bandwidth product. Our next step is to examine the differential input voltage as a function of the output voltage. Differentiating equation 6 we have

$$\Delta V = \frac{1}{\omega u}\frac{dVo}{dt} \qquad (7)$$

This important result shows us that the instantaneous differential input voltage of an amplifier is proportional to the slope (or slew) of the output, with $1/\omega u$ as the constant of proportionality.

If we now look at a real amplifier we will understand what SID is. Fig. 2a is a very simple real amplifier which will serve to demonstrate this. Q1 and Q2 are the differential input pair and Q3, Q4 form a current mirror. This stage is our transconductance amplifier with a transconductance of

$$g_m = \frac{Ik}{2Vt} = \frac{q}{2}\frac{Ik}{kt} \qquad (8)$$

Q5 with its current source load IA and capacitor C forms our integrator. We will neglect the finite d.c. gain produced by R. Ideally Δi is

$$\Delta i = g_m \Delta V = Ik \frac{\Delta V}{2Vt} \qquad (9)$$

but this is only true when ΔV is small. The exact expression for this input stage is

$$\Delta i = Ik \, \mathrm{Tanh} \frac{\Delta V}{2V_t} \qquad (10)$$

Our transconductance stage is not linear and thus will produce distortion when ΔV is large. Equations 9 and 10 are plotted in Fig. 2b.

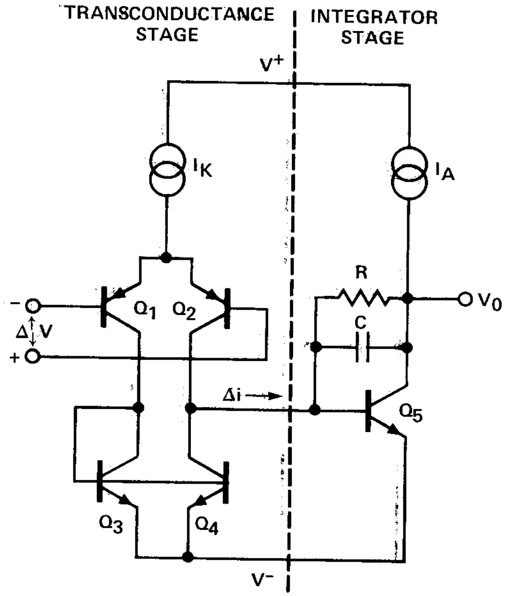


FIGURE 2a REAL AMPLIFIER

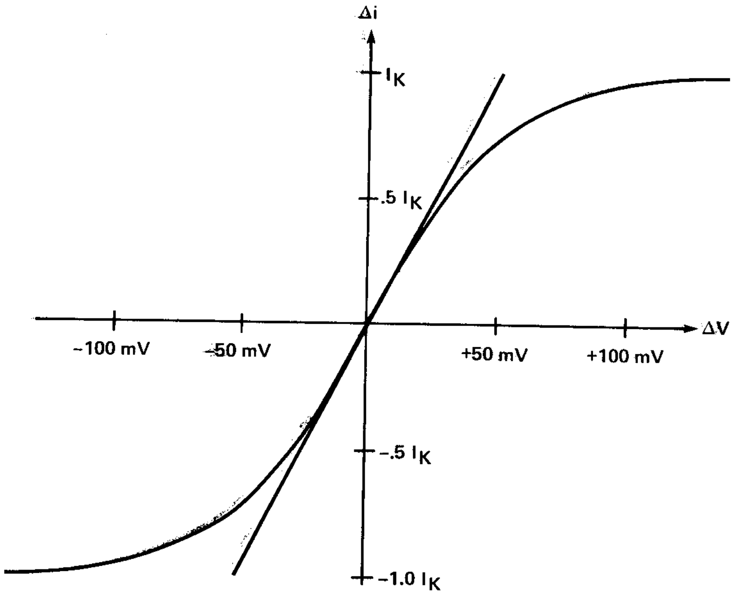


FIGURE 2b TRANSCONDUCTANCE NONLINEARITY

The maximum output current from our input stage is Ik. This determines the maximum rate of change of Vo which is the maximum slew rate of our amp.

$$\text{S.R. max} = \frac{Ik}{C} \qquad (11)$$

How close we are working to the S.R. max is simply

$$\frac{\text{S.R.}}{\text{S.R. max}} = \frac{\Delta i}{Ik} \qquad (12)$$

This ratio is easily measurable from outside the amplifier with a differentiator

$$\frac{\Delta i}{Ik} = \frac{1}{\text{S.R. max}} \frac{dVo}{dt} \qquad (13)$$

A glance at Fig. 2b tells us that operating with a $\Delta i/Ik$ ratio $> .25$ will produce some obvious distortion. This is equivalent to saying that operation at a greater than 25% of the maximum slew rate will produce distortion. This distortion depends solely on the rate of change of the output signal, hence the term "Slew Induced Distortion."

So far we have been talking only of the amplifier with no mention of feedback. We have been discussing the open loop performance. Amplifiers are rarely used open loop so we must turn our attention to the effects of feedback on amplifier performance. An important point to keep in mind as we discuss feedback is that feedback networks are placed around an amplifier and have <u>no effect</u> on its internal performance. Feedback will not effect the validity of any of the equations developed above.

As is well known, feedback will reduce distortion. Let's take a qualitative look at how this happens. A simple feedback network has been placed around our amplifier in Fig. 3. The differential input voltage is

$$\Delta V = \frac{Vin\, R_2 + Vo\, R_1}{R_1 + R_2} \qquad (14)$$

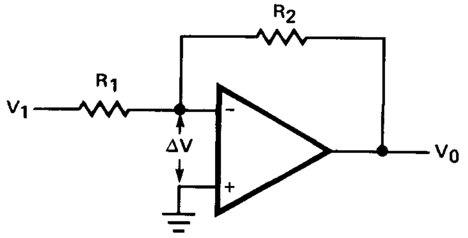
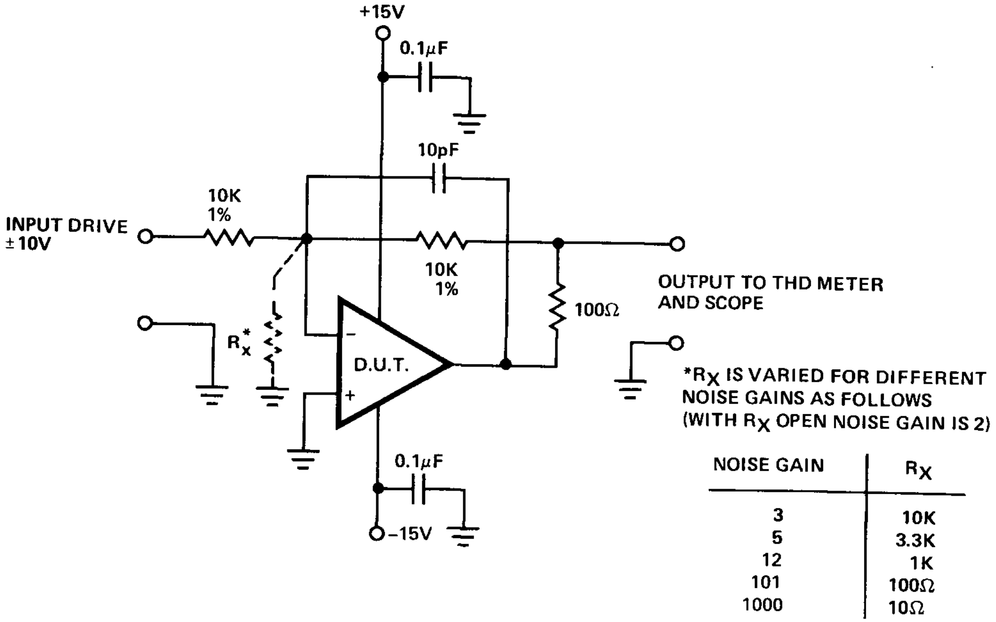


FIGURE 3 AMPLIFIER WITH FEEDBACK



*RX IS VARIED FOR DIFFERENT NOISE GAINS AS FOLLOWS (WITH RX OPEN NOISE GAIN IS 2)

NOISE GAIN	RX
3	10K
5	3.3K
12	1K
101	100Ω
1000	10Ω

FIGURE 5 TEST CIRCUIT FOR SLEW INDUCED DISTORTION

This is the error voltage which we would like to be zero, but will be non-zero if Vo contains a gain or phase error, or distortion. If we operate the amplifier near its slew limit, we know that the amplifier will be very non-linear. The feedback will reduce the non-linearity from Vin to Vout, but it still exists from ΔV to Vout. If the feedback is doing its job and producing a relatively clean signal at Vout, then it follows that the signal ΔV must be distorted. The distortion must be of the proper magnitude and phase to compensate for the amplifier's internal nonlinearity. It is instructive to look at some of these waveforms as shown in Fig. 4. These are pictures of a 748 op amp compensated to unity gain by 30 pf and operated as shown in Fig. 3. The amplifier had the following performance:

$$f_u = \frac{\omega_u}{2\pi} \approx 1.5 \text{ Mhz}$$

$$\text{S.R.} = \begin{array}{l} + .97 \text{ V}/\mu\text{s} \\ - .91 \text{ V}/\mu\text{s} \end{array}$$

The amplifier was operated at full output swing of 20 V p-p. Two frequencies were used, 12.7 Khz and 19.1 Khz. At 20 v p-p these frequencies produce slew rates of $\pm .8$ V /µs and ± 1.2 V /µs respectively. These two frequencies were applied to the closed loop amplifier for gains of 1 and 10. For either gain, the output was a visibly clean sine wave for the 12.7 Khz, $\pm .8$ V /µs signal. The 19.1 Khz, ± 1.2 V/µs signal drove the amp into slew limiting, and this is shown in Fig. 4b. The output slewing waveform was visibly the same for either gain. Fig. 4F summarizes the photos.

The important point to see is that the op amp input, ΔV, becomes highly distorted in an attempt to linearize the response of the closed loop amplifier. As the maximum slew rate is exceeded this process breaks down and the error voltage goes wild. Operation at lower gain (more feedback) yields lower

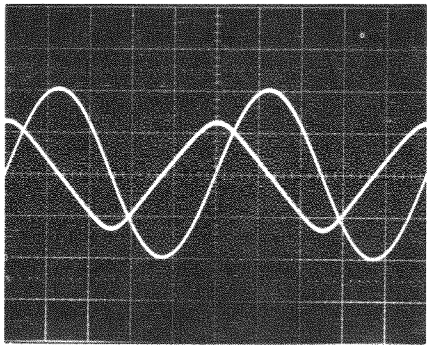


Fig. 4a

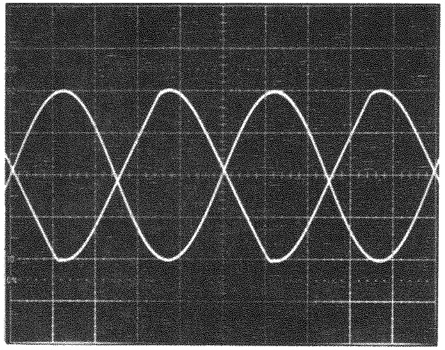


Fig. 4b

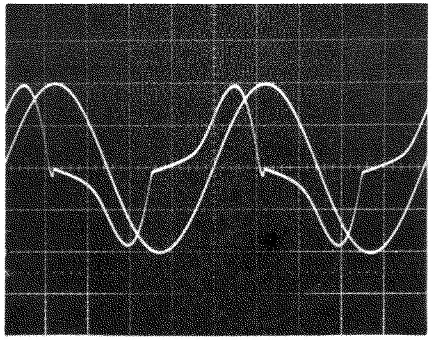


Fig. 4c

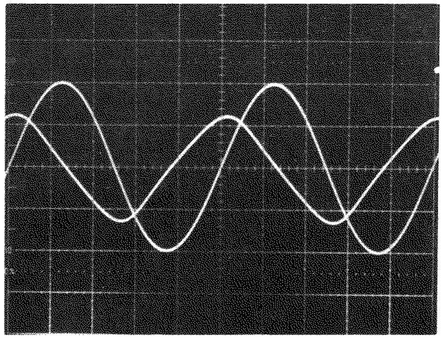


Fig. 4d

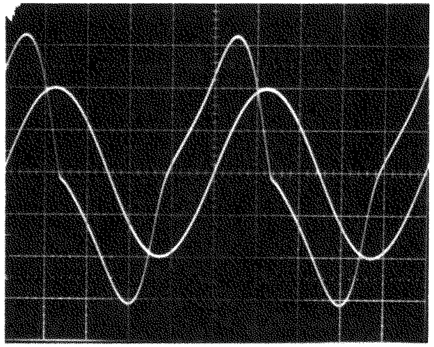


Fig. 4e

Fig.	Gain	S.R.	THD	Trace 1	Trace 2
4a	1	$\pm .8$	$< .05$	Vin 5v/div	Δ V .1v/div
4b	1	± 1.2	3.5	"	Vout 5v/div.
4c	1	± 1.2	3.5	"	Δ V .5V/div.
4d	10	$\pm .8$	.56	"	Δ V .1V/div.
4e	10	± 1.2	4.1	"	"

Fig. 4f

Equivalent Slew Rate of Sine Wave = $2\pi f V_o$

Definition: $f_p = \dfrac{\text{Device Slew Rate}}{2\pi V_o}$

distortion operation, and allows low distortion operation closer to the slew rate limit.

There is nothing particularly unique about slew-induced distortion in audio amplifiers. It can be measured, calculated, and improved upon by using standard techniques that have been available for some time. The only elusive aspect of this form of distortion is that rather than occuring on a peak magnitude (like clipping), it occurs on the rising or falling edge of the waveform. This is due to the fact that the dominant non-linearity in the circuit, the transconductance of the input stage, is followed by an integrating stage. Thus in Fig. 1, if the transconductance stage were overloaded and producing clipped square waves of current output, the integrating stage would transform these square waves into triangle waves at the output. The triangle wave is the ultimate example of gross slewing distortion.

Although slew limiting is most often encountered in amplifiers due to internal I/C relations such as described above, it can also occur due to output current/load capacitance rate limiting, with the end effect being similar. This type of slew limiting can occur in equalized pre-amps which cannot adequately charge frequency shaping capacitors, or power amplifiers which cannot drive capacitive loads due to protection circuitry.

The distortion products produced by SID are measurable either by methods of THD, two tone HF IM, or TIM[16], and in all cases they become significant as the amplifier's inherent slew rate is approached.

Test Methods for SID characterization

A major objective of this study was to develop a reliable and predictive test method for the presence of SID. This objective was not only met, but was done for three different means of measurement, all of which correlate well with

each other, with calculations, and finally, with listening results. The different methods are discussed below.

THD Tests

It has been previously reported that THD testing methods are insensitive to the detection of TIM distortion.[16] In actuality this is only true for spot frequency THD tests. A full output voltage level THD sweep test from 100 HZ to 100kHZ has been found to be the most sensitive test to detect SID in op amps, as it exercises the output rate of change tracking fidelity to a high degree. Unfortunately this form of test is not always directly applicable to power amps, but it is an excellent one for IC op amps.

To implement this test, some important restrictions must be placed on the test circuit. The test configuration must operate in the inverting mode, to eliminate common mode distortion effects which exist when an op amp is operated non-inverting. The magnitude of these effects in some designs can approach that of SID, therefore a non-inverting test is incapable of separating these two components. Similarly, output stage non-linearity must also be minimized by careful restriction of loading to 10K or more. These precautions assure us that we are measuring SID. Distortion produced by poor common mode rejection and output loading should be evaluated separately and are not the subject of this study.

A test circuit which is suitable for SID tests is shown in Figure 5. It is a unity gain inverter, with compensation adjusted for unity gain, except for special cases as noted. Input-output signal levels are full rated voltage swings of ±10V (7VRMS), except as noted.

The device under test (D.U.T.) is operated in this circuit, and the first test made is a check for its actual slew rate. For a given device the actual slew rate can vary markedly from the data sheet value, therefore results can only be correlated by actual measurement, using a fast rise square wave source. Ideally slewing should be symmetric, so the measurement should take note of both (+) and (-) slew rates. After the S.R. test, measurements of swept THD can proceed.

THD data on a 741 IC op amp with a 0.5V/µS SR is shown in Figure 6. This data indicates in the full output curve a characteristic sharp rise from the LF residual level, to a 1% level at the 8kHZ fp frequency, this occurring within only 2 octaves. For lower output levels such as for 2V and 1V RMS, the 1% frequency is proportionally higher, in fact by the ratio of amplitudes. In all three cases the characteristic sharp rise in distortion can be noted as the SR is being approached.

SID, improves considerably for higher slew rate devices, or compensation conditions which result in higher slew rates. In Figure 7, THD data on a 301A amplifier is shown for various compensation/gain conditions with all data referred to a 7VRMS output level.

The first curve is for unity gain compensation, where the SR is 0.9V/µS; the behaviour is similar to but slightly better than the 741 for similar conditions. For the x10 compensation curve, the resulting slew rate is 7V/µS and the performance is much better, with slew limiting not reached until 90kHZ. The improvement is due to the x10 improvement in Gain-Bandwidth product and slew rate.

The third curve is for a x100 compensation/gain, and here slew limiting is not at all evident, as the rise in THD is 6dB/octave, or bandwidth related.

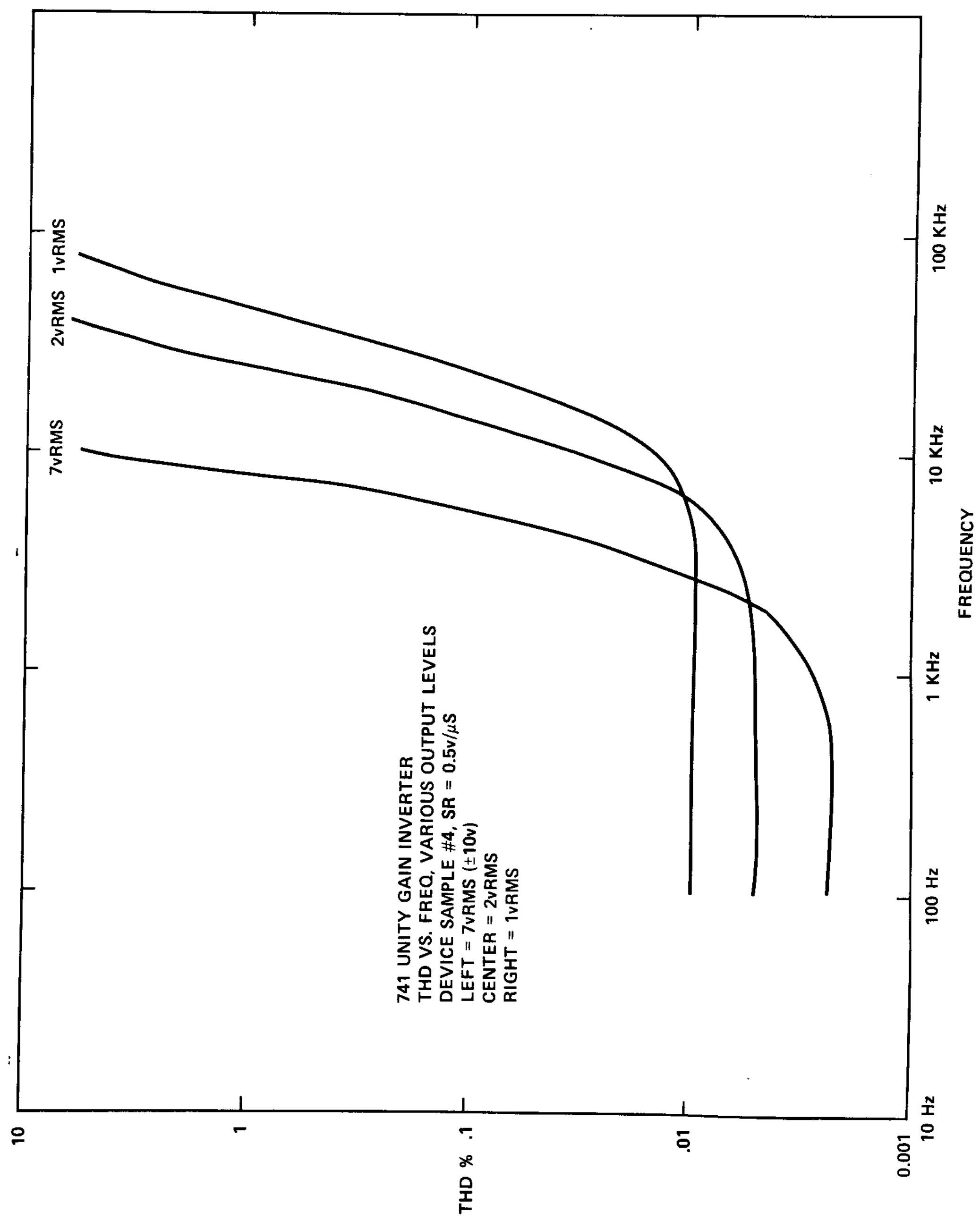


FIGURE 6

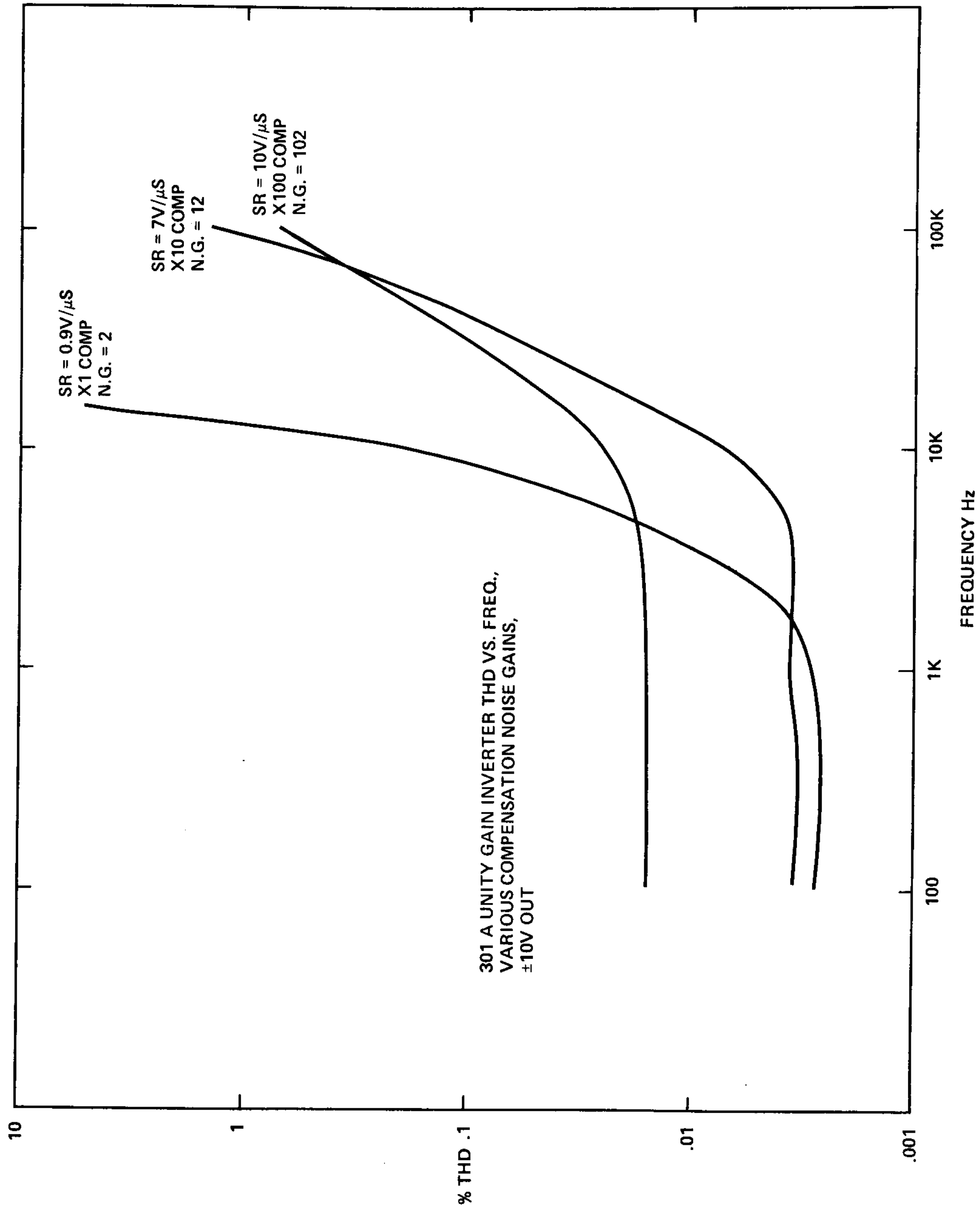


FIGURE 7

Slewing symmetry has a pronounced effect on SID, and SID will only be minimized when the (+) and (-) slew rates are equal. In some IC devices, particularly those which use current mirrors, slew symmetry can be trimmed, which demonstrates this effect as shown in Figure 8.

Here the THD performance of a 301A op amp with a trimmed SR of 0.4V/µS is plotted, and the data indicates an fp of 6.7kHZ which agrees with the theory. For assymmetric slewing however, the distortion generated is much higher and the break point occurs much lower in frequency. This sort of behaviour can be noted in many amplifiers, and those in which slewing is inherently assymetric will not yield as low a distortion as even slower devices which are symmetric. Assymmetric slewing is caused by an assymmetrical transconductance curve and leads to much 2nd harmonic distortion. The 2nd harmonic will rise in amplitude before the 3rd does and is thus detectable at lower levels.

Slew Rate and THD

An interesting demonstration of the effectiveness of slew rate improvement on THD is contained in Figure 9. This data is for the 2720, a programmable IC op amp, where SR can be adjusted via a bias terminal. Shown here is the resulting THD for SR of 0.5, 1.6 and 5V/µS respectively. As can be readily noted, the resulting performance improves directly as SR is increased.

Since the previous examples have indicated a quality of performance directly tied to slew rate, it might seem fair to assume that a very high slew rate is sufficient in itself to achieve this quality. This is not completely the case however, as shown by Figure 10.

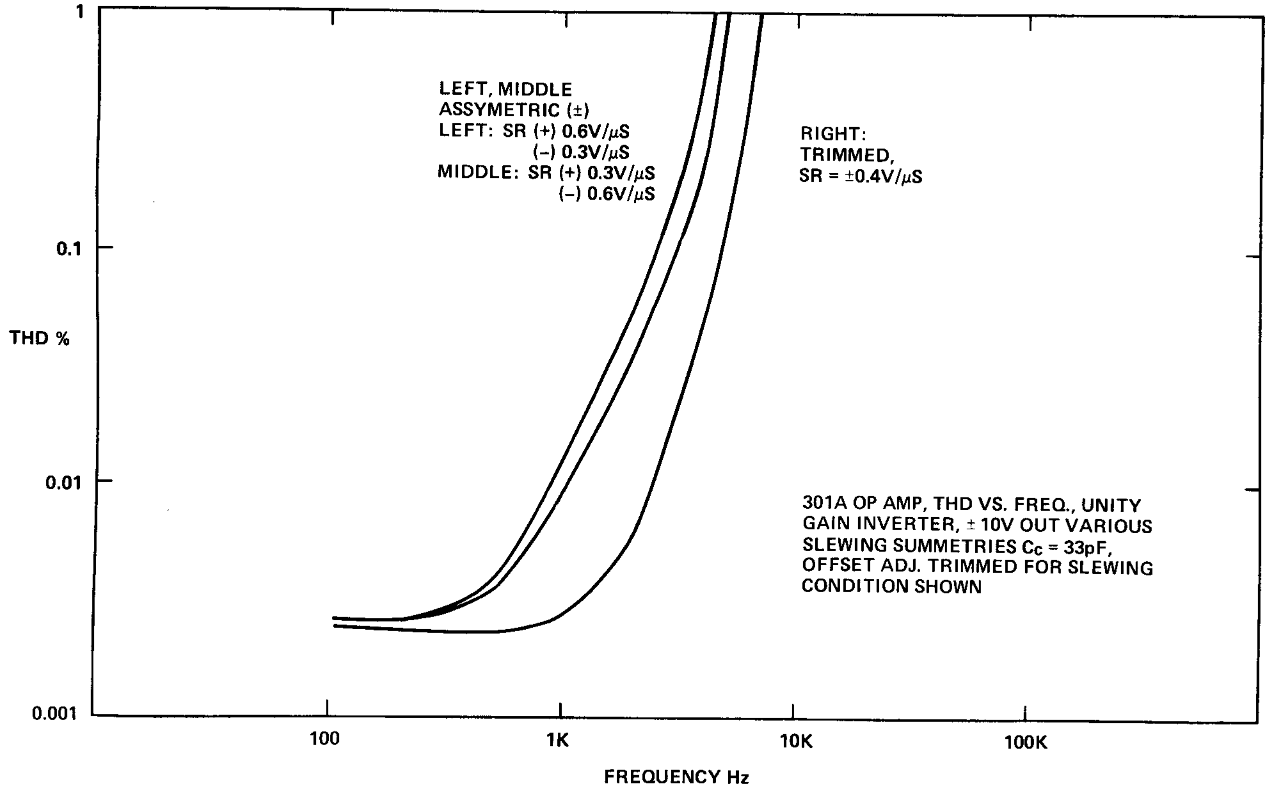


FIGURE 8

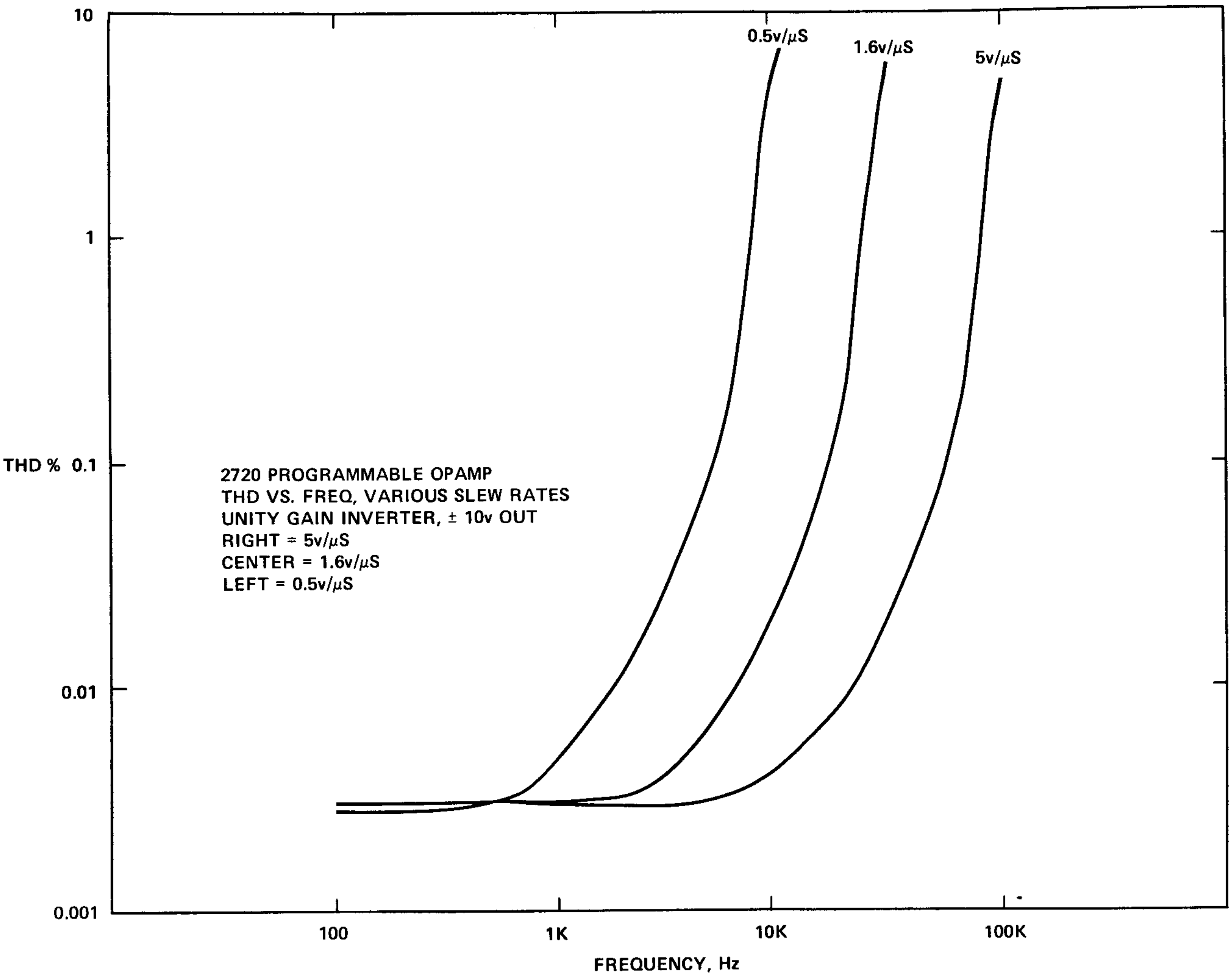


FIGURE 9

This data is THD performance for a class of op amps known as "slew enhanced" types. This form of op amp uses a class B (or AB) input stage to dynamically increase the output current, and thus SR.

In terms of performance, slew enhanced units generally show a low level distortion performance like a conventional op amp up to a point, but complete slew limiting is prevented. The data reflects this, but also shows substantial differences in performance for the various devices tested. Highest performers are those units which show the best low level linearity, and highest GxBW; ie. the x10 531, the 530A and the 538.

At this point, data has been shown which reflects the key behaviour patterns observed in the group of IC samples tested. In general, if the device slew rate is 5V/µS or more, is symmetrical, and does not use slew enhancement, the THD performance will be superlative. This will be evidenced by a THD of 0.01% or less up to 20kHZ, and for the best devices, 0.1% or less up to 100kHZ. Of those tested the best devices in the above terms were: NE5534 (equivalent to TDA 1034) 536, 318, 518, TL084, 3140, 2620, 2525, 301A (feed forward) and the OP-01, Nearly as good were the AD540 and 8007. The common characteristic of all of these amplifiers is their high slew rates; all are 5V/uS or more.

Two-tone HF IM Tests

The second series of tests conducted on the sample group of IC op amps was HF two-tone difference IM, hereafter called simply IM. This type of test also shows SID, as evidenced by IM, to be governed by amplifier slew rate. For these test a 1:1 mixed high frequency tone pair at full output level is swept from 10kHZ to 50kHZ. The difference frequency is maintained @100HZ. All tests were performed in the test ciruit of Figure 5.

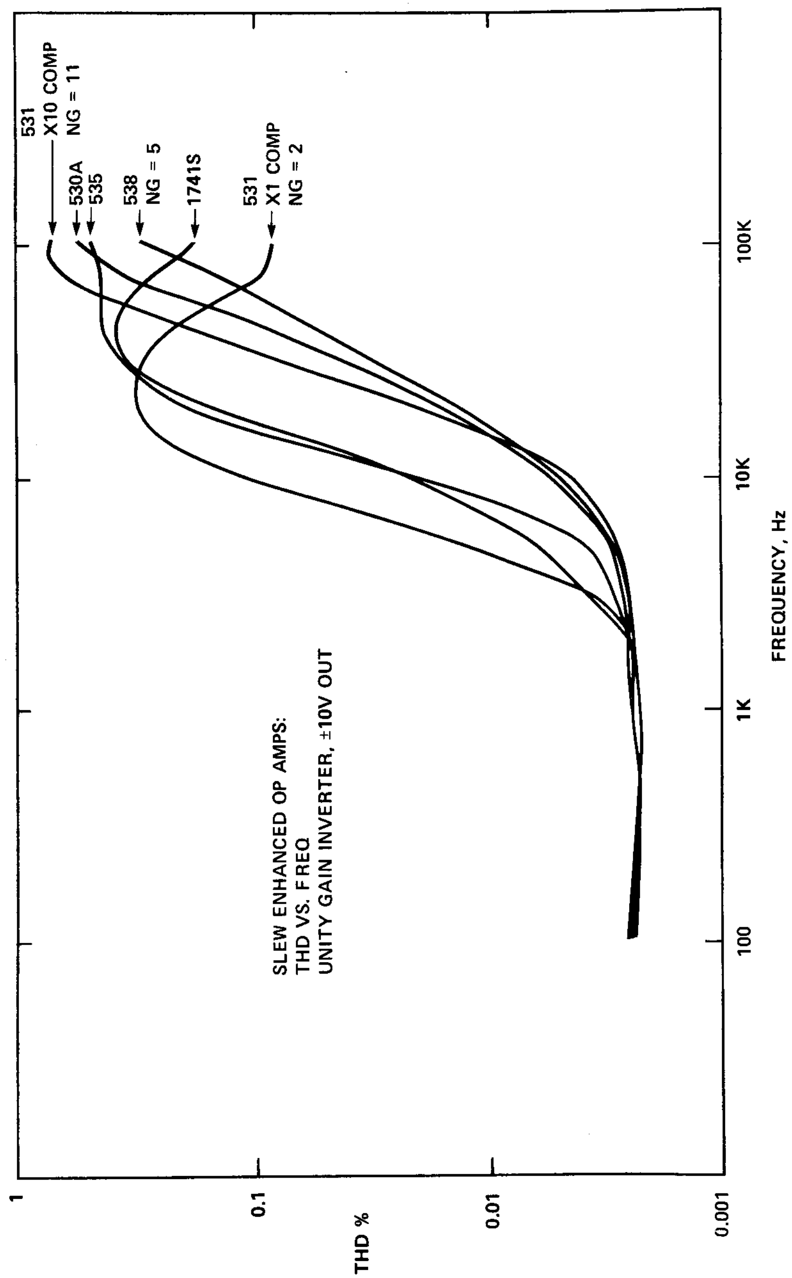


FIGURE 10

Figure 11shows data which indicates the relationship of IM performance and SR. This data was taken with the 2720 programmable op amp, with slew rates of 0.5,1.6 and 5V/µS, conditions similar to Figure 9.

The nature of the IM performance behaviour strongly resembles the data based on THD, showing a similar rise as slew limiting is approached. This behaviour pattern is a characteristic one of IM, just as it is for THD.

Figure 12 shows a composite plot of IM performance for a variety of different IC op amps. The highest performance devices here show data which is at the equipment residual level, while the others show quality generally proportional to slew rate. The notable exceptions to this are the 535, a high speed slew enhanced type, and the 356 an assymetric slewing unit. Both units have high slew rates, but the method of achieving it prevents optimum linearity.

The data from the IM tests follow the same general pattern as THD based data. It is less sensitive, though, due to the fact that it measures even order products and the amplifiers usually (if perfectly symmetrical) generate odd order. This test is quite effective in pinpointing amplifiers which are assymmetrical such as the LF356. A two tone IM test to measure odd order products (2f1-f2) would yield more useful data on the symmetrical devices.

TIM Tests

A selected sampling of devices which had undergone the THD and IM tests were then subjected to the TIM tests as outlined in reference 16. Like the previous tests, the test circuit of Figure 5 was used in these tests. Our results do not directly correlate with those of Reference 16 because we are operating the amplifier with no common mode swing in order to isolate the SID distortion from common mode distortion. Figure 13 summarizes the results of these measurements, for full level tests performed with a 30kHZ square wave band limit.

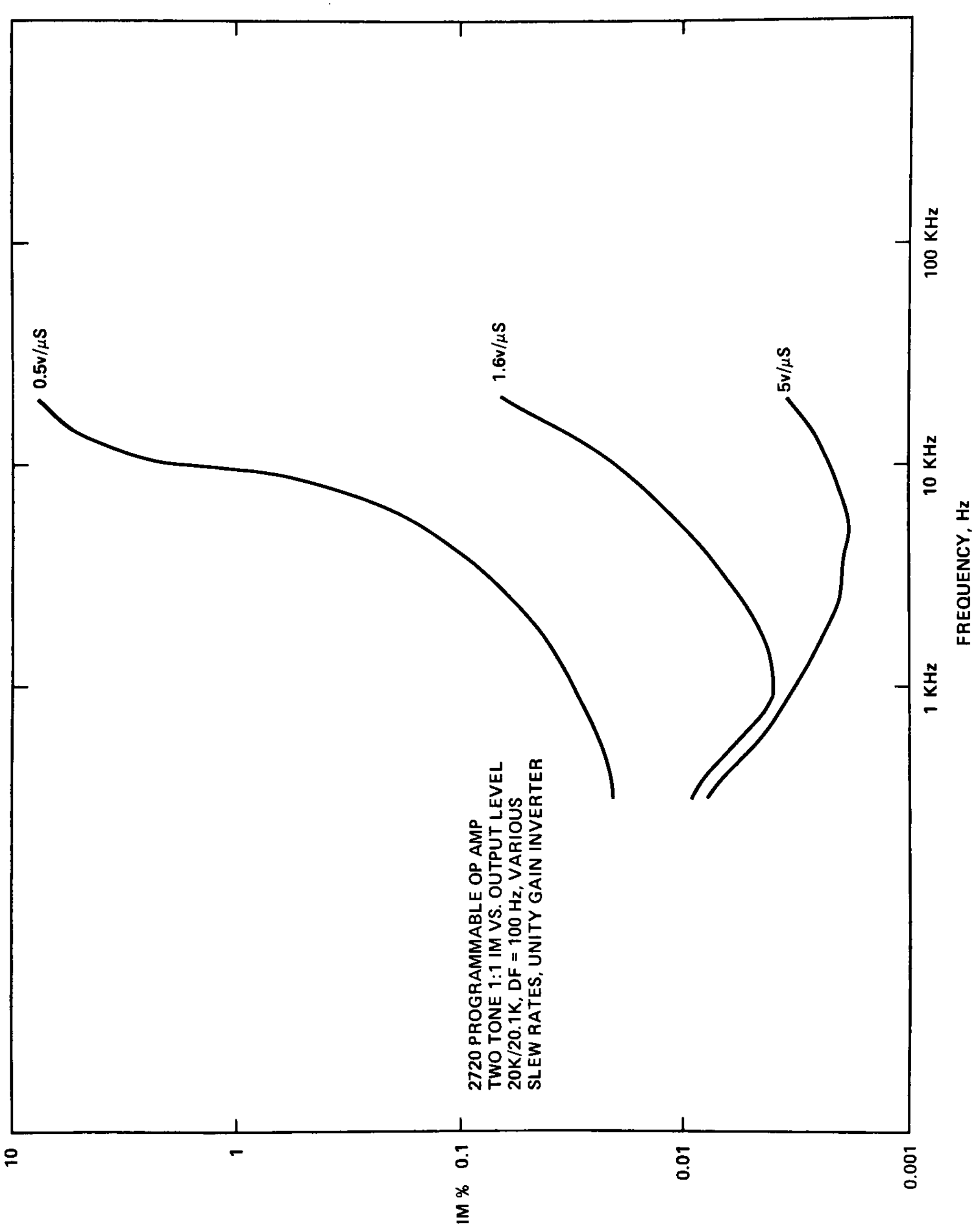


FIGURE 11

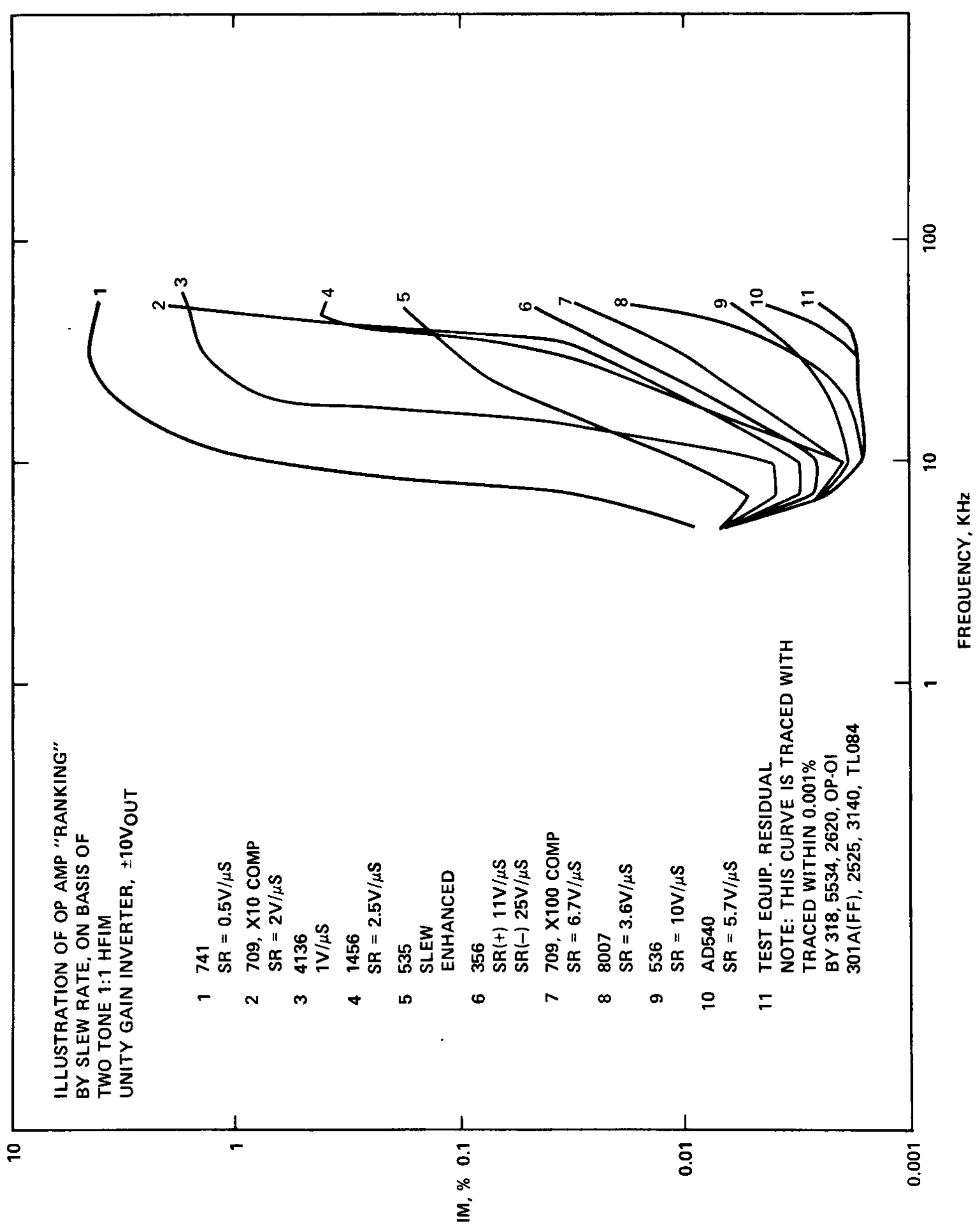


FIGURE 12

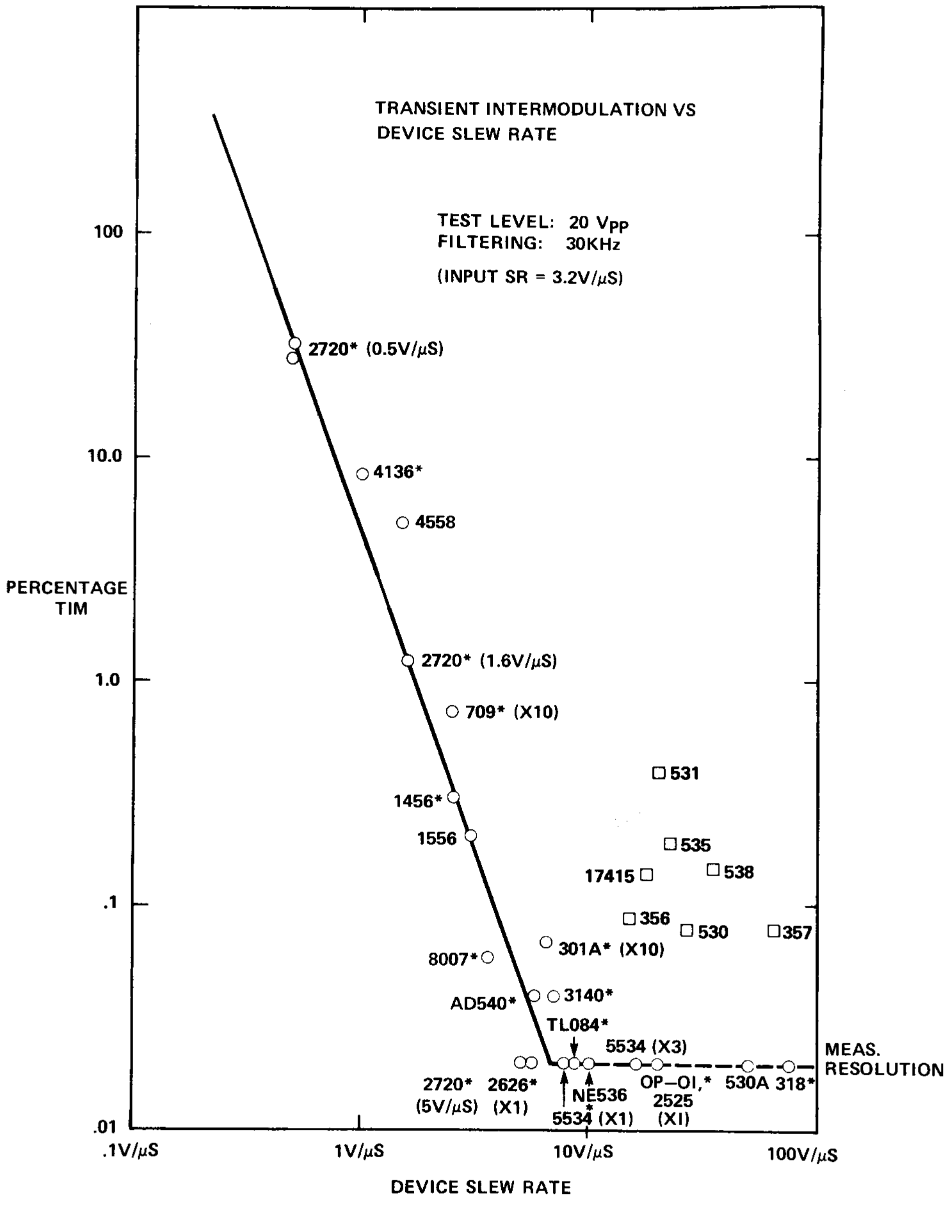


FIGURE 13

The relationship between transient (or dynamic) intermodulation distortion (DIM) and device slew rate capability is clearly exposed by the graph in Figure 13. This graph shows percentage DIM versus device slew rate for all types of devices under one standard test condition. The maximum slew rate of the input sine-square for this case is 3.2V/μS. Thus, the device would have to have a slew rate of at least this much to pass the waveform with unmeasurable distortion. The graph shows that distortion rises above the resolution level around 6.5V/μS, which is roughly twice the slew rate of the input waveform. This indicates that "on the average" a device must have at least twice the slew rate of the input signals to pass them with negligible distortion. As the slew rate capability of the devices falls below 6.5V/μS the graph is seen to rise linearly to very high amounts of distortion. A "best" straight line drawn through the data points turns out to have a slope of 3:1 on the logarithmic coordinates. This indicates that DIM varies as the third power of the ratio of the input slew rate to the device slew rate. A simple equation that expresses this relationship would be

$$\% \text{ DIM} = K\left[\frac{\text{SR of signal}}{\text{SR of device}}\right]^3 \qquad (15)$$

where K = 0.16% for our data

This relationship is extremely important to audio designers as it indicates how transient intermodulation varies with the input signal levels.

It should be noted from Figure 13 that there are devices that do not fit the characteristic straight line relationship between distortion and slew rate. These devices are grouped to the right of the line and generally show excessive distortion for their high slew rate capability. With the exception of the Bi-FET devices (356,357), all of these are slew-enhanced op amps. They feature an input transconductance that varies with level to produce rapid slew rates for large signals.

Unfortunately, the changing transconductance gives rise to a crossover type of distortion mechanism. Since, for small signals their slew rate capability is low, they begin to produce distortion for relatively slow waveforms. As the speed and amplitude of the input is increased, the performance of the device gets better, and it is more capable of producing the required output. Thus at high slew rate inputs, the distortion doesn't increase, it merely remains the same percentage as it was under low slew rate conditions. We found that under varying input slew rate waveforms, the output spectrum of the slew-enhanced devices remained fairly constant, only the relative magnitudes of the individual distortion products varied up and down. Increasing the input slew rate caused some distortion terms to increase, and some to decrease, but the magnitude remained fairly constant. It is interesting to compare this behaviour with the leveling off of THD observed in the THD tests.

The BiFET devices also did not fit on the characteristic straight line, but they suffer from a different type of problem than the slew-enhanced circuits.
The Bi-FET's only showed even order distortion falling on the square wave harmonics.
No other intermodulation products were produced as the slew-enhanced devices did.
The Bi-FET devices seem to alter the symetry of the waveform, indicating that some kind of lop-sided non-linearity is in action. This theory is supported by the basic slew rate of the 356 which is 11 V/μS positive and 27V/μS negative. The problem experienced by the Bi-FETs is not inherent in all FET op amps, by any means. The 536, an older design, had DIM levels below the resolution of our measurement equipment.

Devices which are capable of differing slew rates, such as the 2720 and 301A, show TIM performance which improves as slew rate is increased. To examine the effects of open loop bandwidth and the degree of feedback as design criterions for low TIM, several specific tests were performed. The results of these are the spectrum plots shown in figures 14, 15.

Figure 14 shows comparative performance for two different op amps for conditions of 10V output and a 30kHZ band limit. The 0.8V/uS device (a 741) clearly shows strong TIM, but the 10V/µS device (a 536) shows a spectrum which is indistinguishable from the input. Open loop bandwidth of both devices is less than 20hZ, feedback is nearly 100dB at low frequencies, and GxBW is 1 mhz.

Figure 15 shows a performance comparison for 20V, 30kHZ band limit conditions, with slew rates adjusted to 0.5,1.6 and 5V/µS using the 2720 device. It is clear that TIM is reduced as the slew rate is increased. For these conditions, device open loop 3dB bandwidth is for all cases less than 200HZ, and feedback is nearly 100dB at low frequencies.

It is apparent from these two tests and others made that the TIM test performance is strongly effected by slew rate, just as is THD and IM. There is no directly measurable or obvious sensitivity to open loop bandwidth. Gain bandwidth product and loop gain (feedback) effect TIM performance, as they do THD and IM in that they effect how close to slew limit one can work before distortion rises.

A further demonstration of how TIM behaves similar to THD and IM performance is contained in Figure 16. This data is based on the common condition of a 30kHZ band limit but with TIM plotted versus output amplitude. To show the similarity, two different slew rate devices are used, 0.5 and 1.5V/µS. At low signal levels TIM is at a very low level; as the output signal level is increased, TIM shows a rapid rise, similar in behaviour to THD and IM.

Comparison of Tests

If these three test methods are compared on a common base, it is possible to see a definite pattern in their behaviour. This is shown in Figure 17. For this

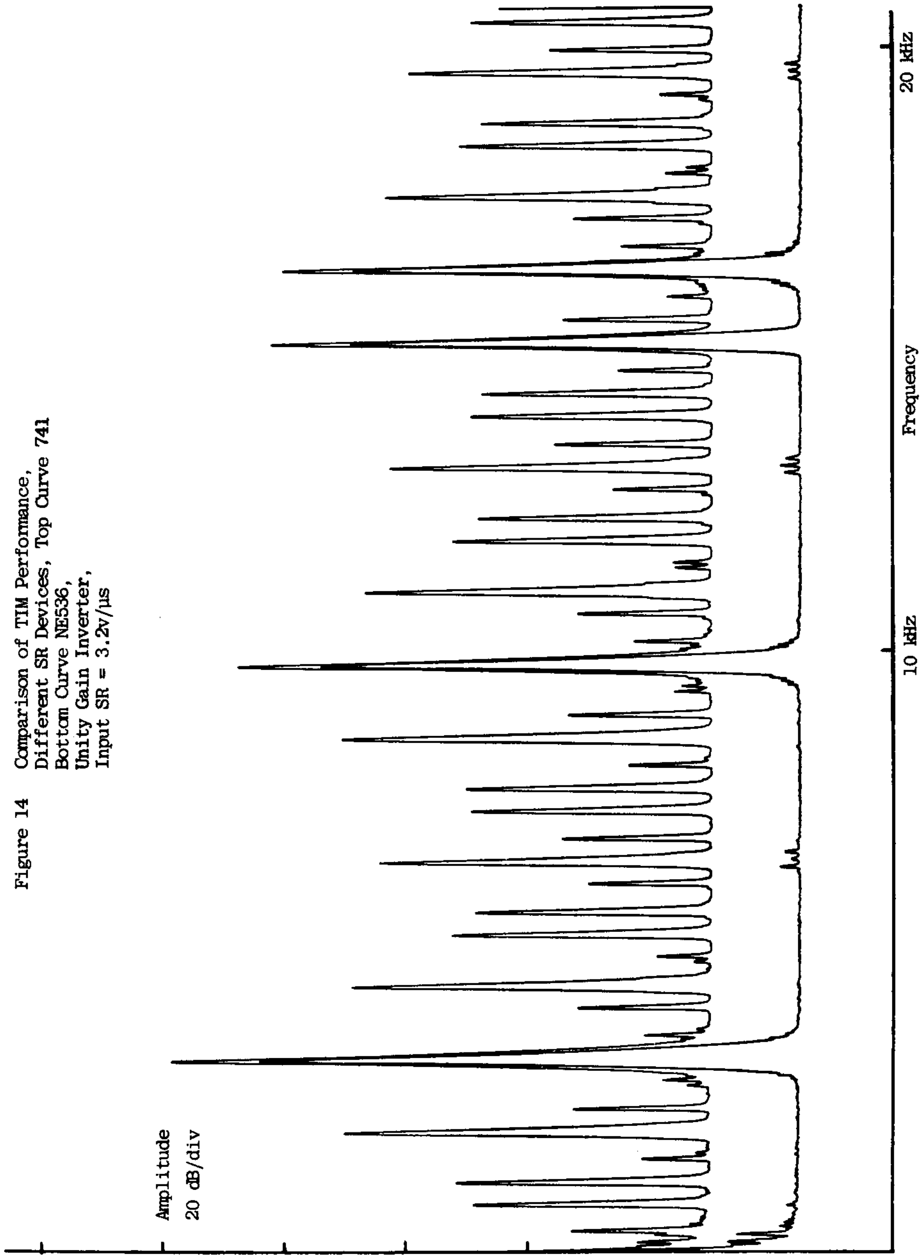


Figure 14 Comparison of TIM Performance,
Different SR Devices, Top Curve 741
Bottom Curve NE536,
Unity Gain Inverter,
Input SR = 3.2v/µs

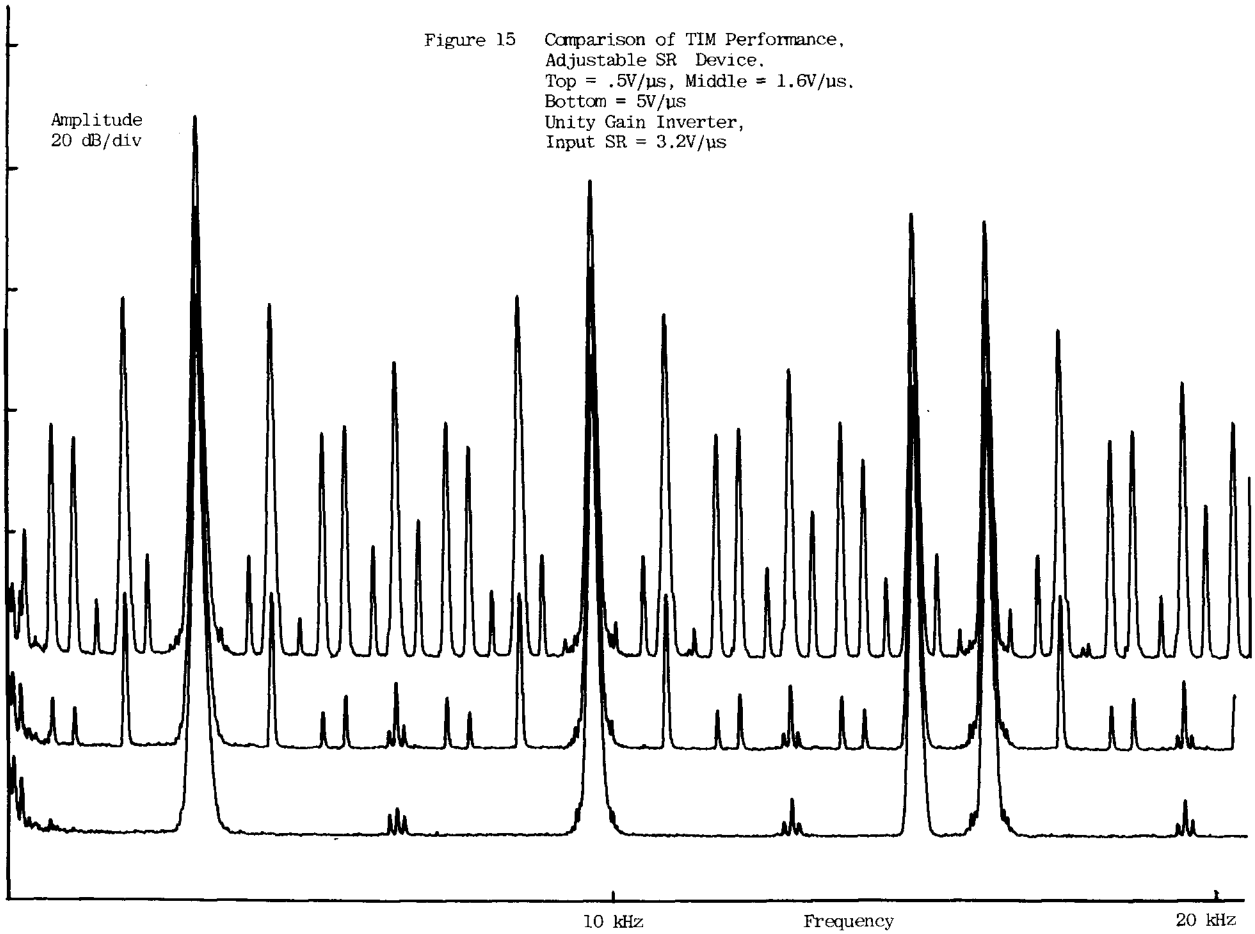


Figure 15 Comparison of TIM Performance,
Adjustable SR Device.
Top = .5V/µs, Middle = 1.6V/µs.
Bottom = 5V/µs
Unity Gain Inverter,
Input SR = 3.2V/µs

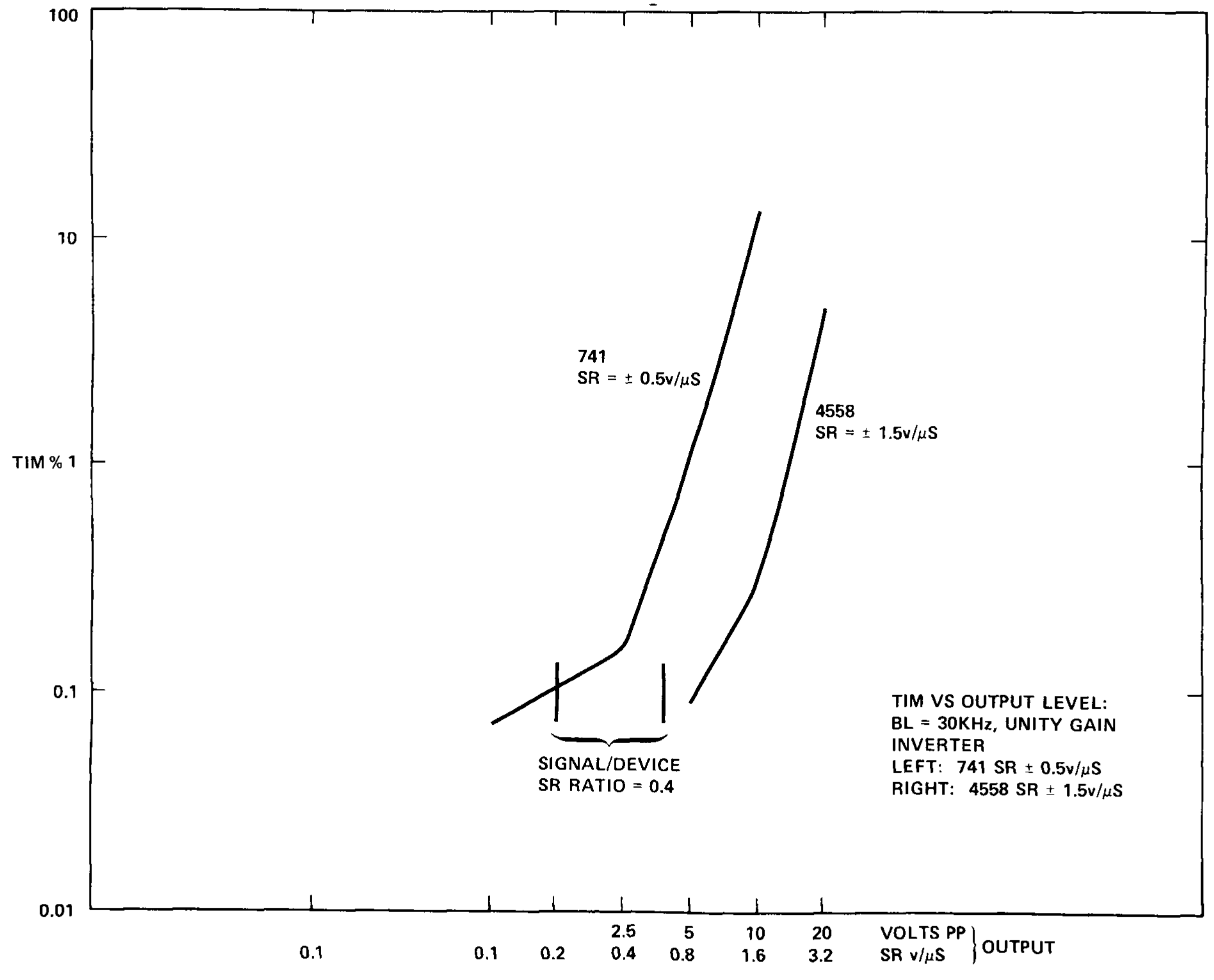


FIGURE 16

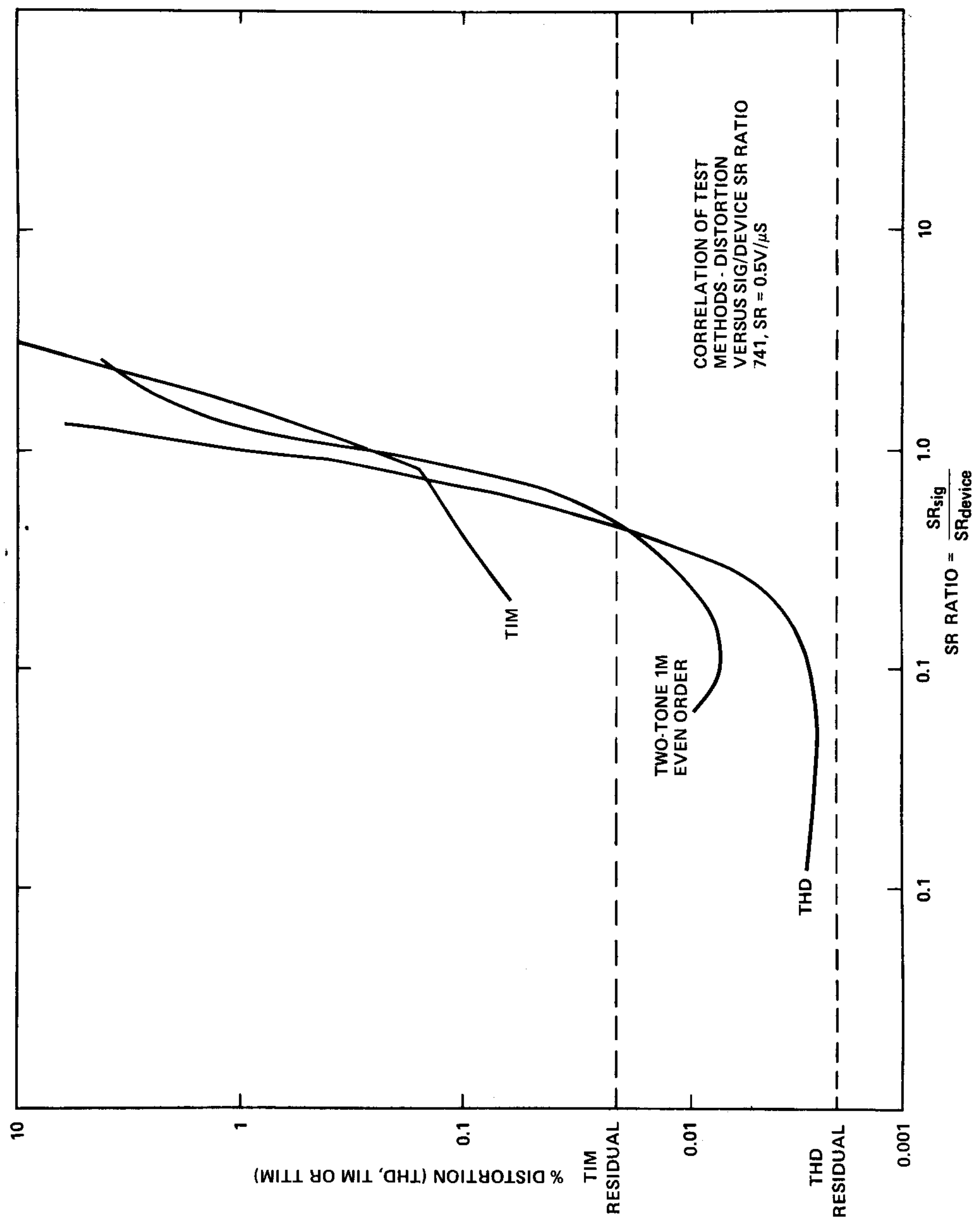


FIGURE 17

figure, the horizontal axis is normalized in terms of the ratio of the signal slew rate to that of the device. By this means it is possible to see just how the various forms of distortion behave as the device slew is taxed, and also to indicate the relative sensitivity of the three test methods.

The THD method shows the widest dynamic range of the 3 methods, and gives the highest percentage distortion at unity slew rate (1%.) The anomalous slope for the TIM test is due to our detection of some 2nd order low level non-linearities in the 741 tested. This produced a 2nd harmonic of the square wave which we were able to detect in the output spectrum. Since the TIM distortion number is normalized to the 15khz sine wave amplitude, and the square wave amplitude is 12 dB larger, the distortion shows up a factor of 4 larger than it should. Our experiences showed that it was very difficult to detect SID with the sine-square TIM test at slew rates under 1/2 of the maximum.

Unfortunately, there is a serious problem with the sine-square test method, which became apparent after evaluating some of the best op amp circuits. The problem concerns amplifier distortion products which are coincident with the even order distortion products of the square wave generator. Theoretically, a square wave should consist only of odd order harmonics of the fundamental frequency. Practically, every generator has a very slight assymetry in its square wave output, which creates small but definitely measureable amounts of even order distortion. Typical amounts for a general purpose square wave generator are 50 to 60 db down from the fundamental. Thus, if one was measuring a very good amplifier that had only small even order distortion products falling on the square wave harmonics, the true distortion of such a case would be masked by the generator and therefore unmeasureable. The conclusion might then be erroneously drawn that the amplifier was free from transient intermodulation distortion, when actually the amplifier was producing small amounts of distortion below the threshold of measurement.

One might question at this point that any amplifier that would produce distortion products coincident with the square wave harmonics should also produce other intermodulation products of comparable magnitude, that could be readily measured. This simply is not the case and can be easily demonstrated, by testing a 356 or an 530A. Both of these amplifiers show only even order square wave products, even at the severest slew rate test. To accurately measure these two devices, a square wave generator with even order products down at least 90db is required. In this series of tests, this was obtained by carefully adjusting the symmetry of our square wave generator at periodic intervals. Only when we reduced the generator's even order distortion did we begin to see differences between the best op amp circuits, that typically had only even order distortion products. The magnitude of these even order products for the best circuits were from 0 db to 6db greater than the generator residuals, and in many cases required detailed comparison of the input and output spectrum over several runs to verify that the products were in fact actually there.

The two tone difference IM test is much more sensitive to even order distortion than the sine-square test. Where it was difficult to detect distortion in the 356 with the TIM test, the IM test found it easily (Fig. 12.) It is probable that a two tone IM test set up to look for odd order products would show superiority for finding odd order distortion products. The main attraction of the TIM test is that it allows a quick qualitative look at an amplifier's performance; if that is, one has a spectrum analyzer handy.

THD evolves as the most desirable test method. It is sensitive and equipment is common. But, when a limited bandwidth circuit is being evaluated, one must use some form of IM test. It appears that maximum sensitivity can be obtained with the use of only two tones to isolate a given product.

A very simple test to determine if an amplifier is approaching slew rate is to look at the phase shift through the amplifier as a function of amplitude. The phase shift of an amplifier should not depend on amplitude, only frequency. However, when an amplifier approaches slew limiting the phase shift will change[29]. Implementation of this test is simple. Pass the highest frequency of interest through the amplifier and monitor the phase shift as the amplitude is raised. If the phase changes at large amplitudes, then SID is being produced. To date no work has been done to evaluate the sensitivity of this test method for audio amplifiers operated below the slew limit.

From this data it can be concluded that SID is a relevant factor and easily measurable evidence of it is produced beginning (for low GxBW devices) at as low as 20% of the devices slew rate, or at a slew rate ratio of .2. High frequency THD is a simple method of measuring SID.

Calculation of Slew Induced Distortion

Thus far, little has been said in the literature about how to calculate slew-induced or transient intermodulation distortion. This is no doubt due to the complexity of the problem, especially handling the frequency dependence of the amplifier stages and the incorporation of feedback. There is however, a straight forward technique that can be used to find closed form expressions for every possible harmonic or intermodulation distortion component. The technique involves forming a Volterra Series to characterize the output as a function of some input variable (28). The coefficients of the Volterra Series can then be used to find the magnitude and phase of all distortion products. This technique has been widely used to predict distortion in radio frequency circuits with a high degree of accuracy.

Unfortunately, it takes more time and space to explain the technique itself than it does its application to a given problem. For this reason, we have decided not to present a full analysis at this time. However, with appropriate assumptions and simplifications, many useful features of the Volterra Series' technique can be used to find approximate expressions for SID. These are conceptually easier to understand and are quite accurate for relatively small distortion conditions.

Consider a 741 type operational amplifier, which can be broken down into two basic stages, an input transconductance amplifier, and an integrating amplifier. These are shown in Fig. 18.

The transconductance stage is assumed to be the dominant non-linearity and consists of a symetrical saturating type of characteristic which is independent of frequency.

The non-linear characteristic (formed by a double differential pair) is modelled as a current source output Δi, for an input differential voltage ΔV, and can be represented by equation (16)

$$\Delta i = Ik \tanh\left[\frac{\Delta V}{4Vt}\right] \qquad (16)$$

$$\text{where } Vt = \frac{KT}{q} \cong 26 \text{ MV at } 300\ ^{o}K$$

$$Ik = \text{bias current of stage}$$

The graph of equation (1) is shown in Fig. 19.

Equation 16 and Fig. 19 differ from equation 10 and Fig. 26 in our previous example because the 741 input stage has a pair of transistors on each side. Equation (16) in its present form will not allow closed form expressions for distortion. It must be expressed as a truncated power series with variable ΔV, to complete the calculations. This is shown in equation (17).

$$\tanh x = x - \frac{X^3}{3} + \ldots\ldots + \ldots\ldots \qquad (17)$$

Thus combining (16) and (17) we have

$$\Delta i = Ik \tanh\left[\frac{\Delta V}{4V_t}\right] \cong Ik\left[\left(\frac{\Delta V}{4V_t}\right) - \left(\frac{\Delta V}{4V_t}\right)^3 \frac{1}{3} + \ldots\right] \qquad (18)$$

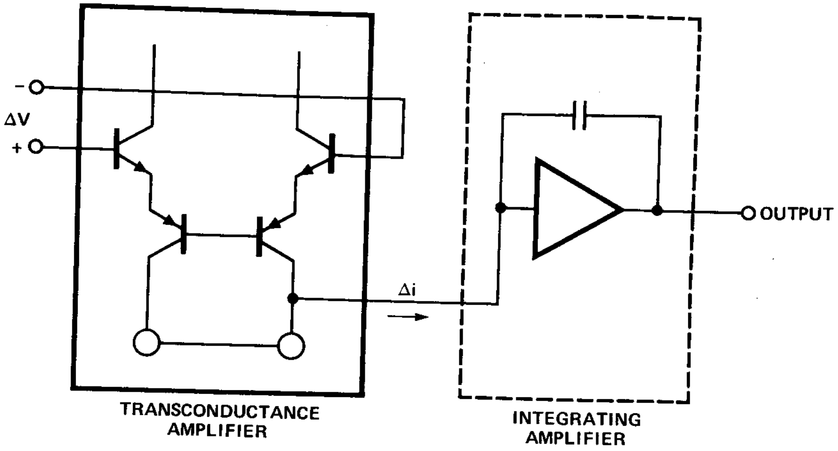


FIGURE 18

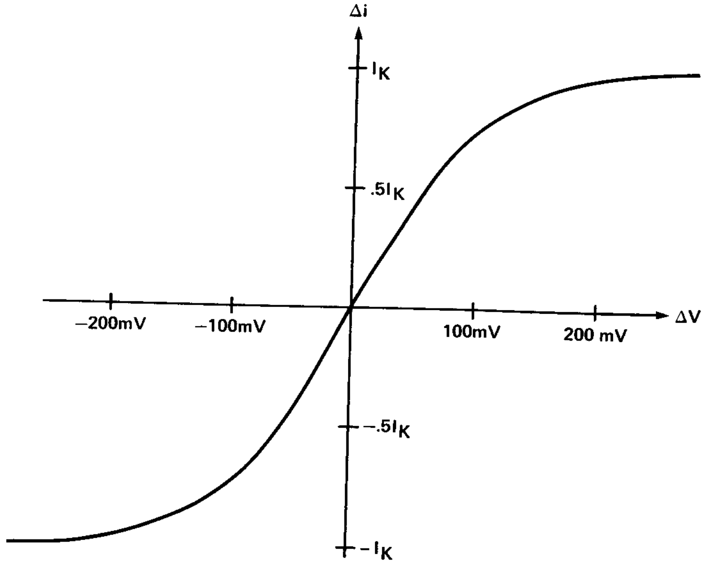


FIGURE 19

The first term in the power series is the desired linear component, and the cubic term (and other higher order terms) form undesirable distortion products. Distortion will eventually be calculated from (18) after making some additional necessary assumptions.

The second stage in the 741, the integrator, is assumed to be ideal, and have a gain characteristic G(f) which is proportional to 1/f. This is expressed by (19)

$$G(f) = \frac{K_2}{f} \qquad (19)$$

The $\pi/2$ phase shift is neglected in (19) since only the magnitude is needed for the distortion calculation. The constant K_2 is determined by the overall gain of the composite amplifier which must be approximately unity at a frequency of 1 MegHz to make our circuit model represent the performance of a real 741 type op amp.

The actual gain characteristic of a 741 op amp is summarized by the Bode plot in Figure 20. For most audio frequency calculations, it is convenient to neglect the low frequency pole at 10 Hz, and to assume infinite dc gain and a constant gain-bandwidth product. This has a negligible effect on calculations since distortion is only affected by the magnitude of the gain bandwidth product. The open loop gain for this approximation is specified by equation (20)

$$\text{open loop gain} = \frac{V_{out}}{\Delta V} = \frac{10^6}{f} \qquad (20)$$

By combining equations (20), (19) and (18), the constant K_2 can be expressed in more familiar terms. At a frequency of 1 MegHz we have:

$$\frac{V_{out}}{\Delta V} = 1 = \begin{bmatrix}\text{gain of} \\ \text{transconductance} \\ \text{stage}\end{bmatrix} \begin{bmatrix}\text{gain of} \\ \text{integrator}\end{bmatrix}$$

$$1 = \frac{Ik}{4V_t} \left[\frac{K_2}{10^6}\right] \qquad (21)$$

$$K_2 = \frac{4V_t}{Ik} \times 10^6 \qquad (22)$$

$$\text{And thus } G(f) = \frac{4V_t \times 10^6}{I_k} \times \frac{1}{f} \qquad (23)$$

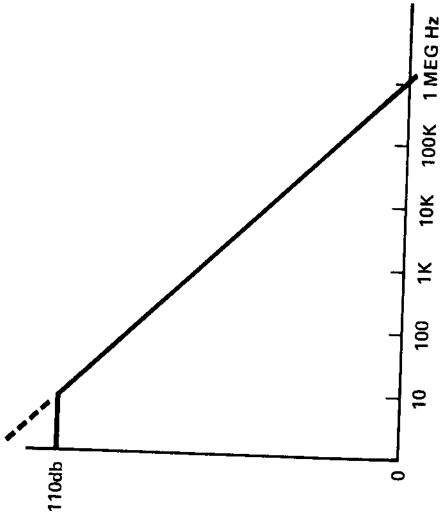


FIGURE 20

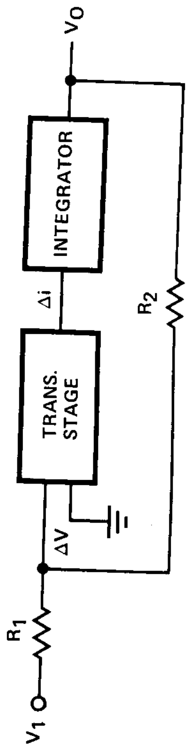


FIGURE 21

The 741 type op-amp that has been developed thus far, is now placed in an inverting gain configuration with resistive feedback components. The feedback network is assumed to be linear and independent of frequency. The circuit used for distortion calculations is shown in Fig. 21.

In this circuit, a feedback factor H can be specified as a function of R_1 and R_2

$$H = \frac{R_1}{R_1 + R_2} \qquad (24)$$

Since the closed loop gain is equal to R_2/R_1, we have

$$H = \frac{R_1}{R_1 + R_2} = \frac{1}{1 + |G|} \qquad (25)$$

For inverting gains of 1, 10, and 100 the factor H is 1/2, 1/11 and 1/101, respectively.

Additional assumptions that must be made to simplify calculations are:

1) Small distortion conditions exist (<1%.) This enables a power series expansion of the transconductance non-linearity.
2) The distortion only consists of odd order products because of symmetry, and because of 1) the distortion is dominated by third order terms.
3) The distortion is reduced by the magnitude of the loop gain at the frequency of the distortion product.

A harmonic distortion analysis will be developed here to compare with measured data, although an intermodulation analysis could also have been pursued. The final result will solve for harmonic distortion (which is dominated by the third harmonic) as a function of output voltage level, frequency, and feedback factor (or closed loop gain.)

The following method will be used to solve for harmonic distortion. First, an output level Vo, and frequency f will be specified. Then using (20), ΔV will be calculated and used in (18) to find open loop distortion. Finally the loop gain will be computed and used to predict the closed loop distortion.

For a sinusoidal output voltage of Vo cos $2\pi ft$, we can compute ΔV from (20)

$$\Delta V = \frac{Vo \cos 2 ft}{(10^6/f)} \qquad (26)$$

If this ΔV is substituted into (18) and simplified, the resulting equation will show an open loop distortion ratio of:

$$\frac{\text{magnitude of 3rd harmonic}}{\text{magnitude of fundamental}} = \frac{\left(\frac{V}{4V_t}\right)^2}{12} = \frac{\text{Distortion}}{\text{(open loop)}} = \frac{1}{12}\left(\frac{Vo \quad f}{4V_t \text{ X } 10^6}\right)^2 \qquad (27)$$

The open loop distortion is reduced by the loop gain at the third harmonic frequency, 3f, and by the integrator frequency response which attenuates the third harmonic by a factor of 3. The loop gain at frequency 3f is

$$\text{loop gain} = \left(\frac{I_k}{4V_t}\right) \text{ X } \left(\frac{4V_t \text{ X } 10^6}{I_k \ 3f}\right) \text{ X } H = \frac{10^6}{3f} H \qquad (28)$$

Therefore the closed loop distortion is

$$\frac{\text{distortion}}{\text{(closed loop)}} = \frac{\text{distortion (open loop)}}{\text{loop gain}} = \frac{1}{3}\left[\frac{\frac{1}{12}\left(\frac{Vo \ f}{4V_t \text{ X } 10^6}\right)^2}{\left(\frac{10^6 \ H}{3f}\right)}\right] \qquad (29)$$

$$\text{THD (3rd)} = \frac{Vo^2 \ f^3}{12(4V_t)^2 \text{ H X } 10^{18}} = \frac{Vo^2 \ f^3}{1.29\text{X}10^{17} \text{ H}} \qquad (30)$$

Equation (30) shows that harmonic distortion should vary directly with the cube of the input frequency, directly with the square of output voltage, and inversely with the feedback factor H. In order to test the accuracy of this equation, calculated data for distortion was compared directly with measured THD data from a 741 amplifier. Figures 22, 23 and 24 compare calculated and measured distortion for a constant amplitude, swept frequency test condition, for three values of feedback factor H. Figure 25 compares calculated and measured distortion for a constant frequency, swept amplitude test condition, also for three values of feedback factor. The agreement is generally good and is excellent for the swept frequency tests. At lower distortion levels, the agreement deteriorates due to measurement resolution limits. At higher distortion, the agreement deteriorates due to large distortion conditions; that is, the fundamental assumptions in developing the calculation are violated. The anomalous behavior of the G = 100 test results are due to a low closed loop bandwidth of 10KHZ, and the absence of loop gain at these frequencies. Figure 25 also indicates same form of crossover distortion that dominates at low signal levels, and masks the true distortion characteristics. It should be clear from all the figures that increasing feedback reduces distortion.

The demonstrated accuracy of equation (30) in predicting harmonic distortion in a 741 amplifier, leads to some powerful conclusions concerning slew-induced distortion.

1) It means that slew-induced distortion can be modelled and calculated using straight-forward harmonic distortion techniques.
2) It emphasizes that there is nothing new, unique, or mysterious about slew-induced or transient intermodulation distortion.

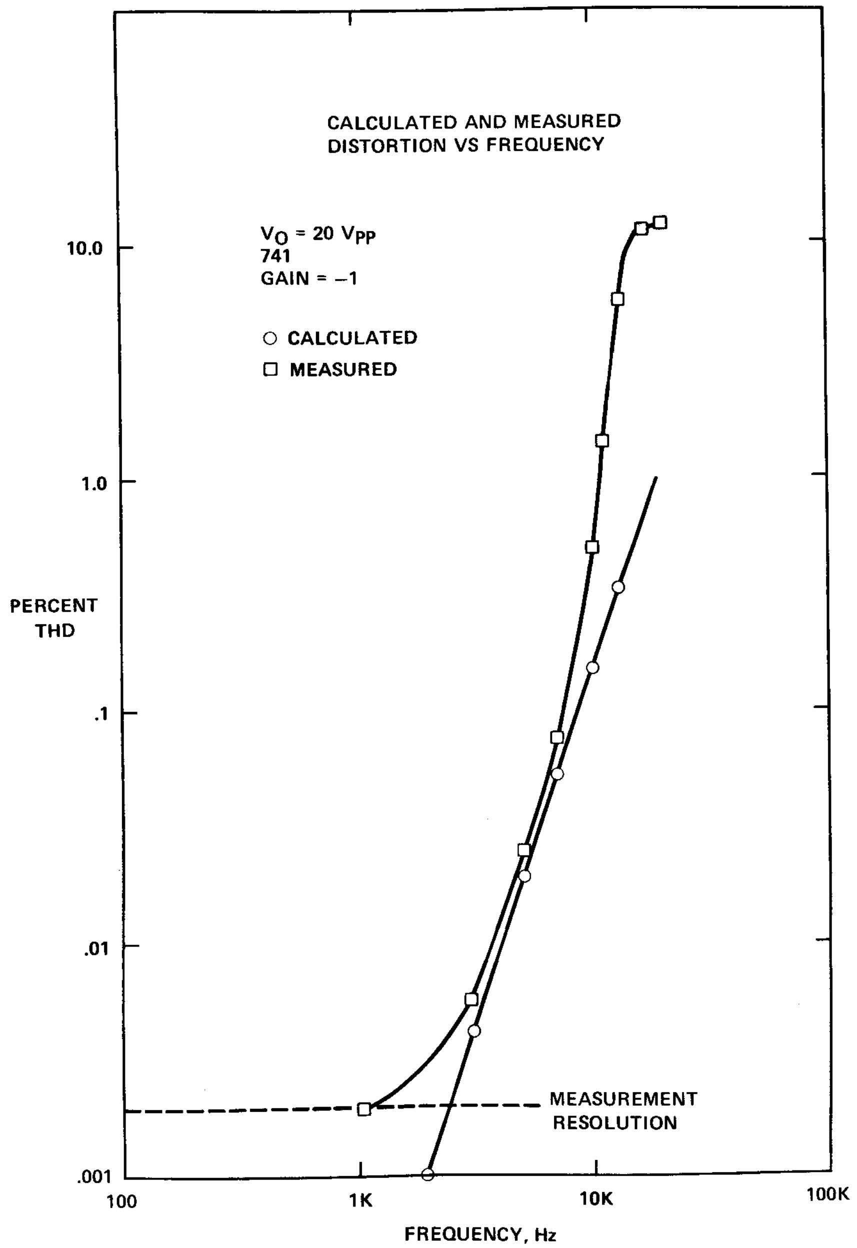


FIGURE 22

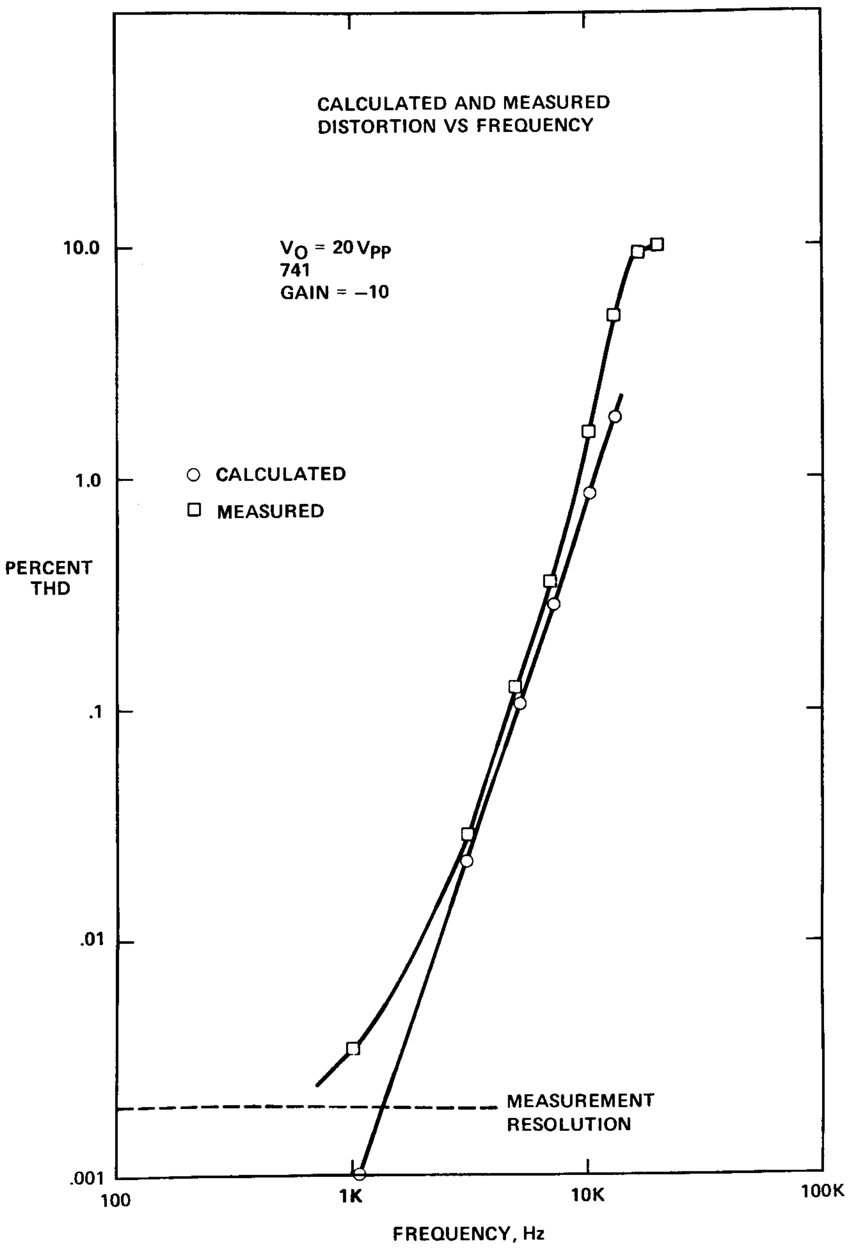


FIGURE 23

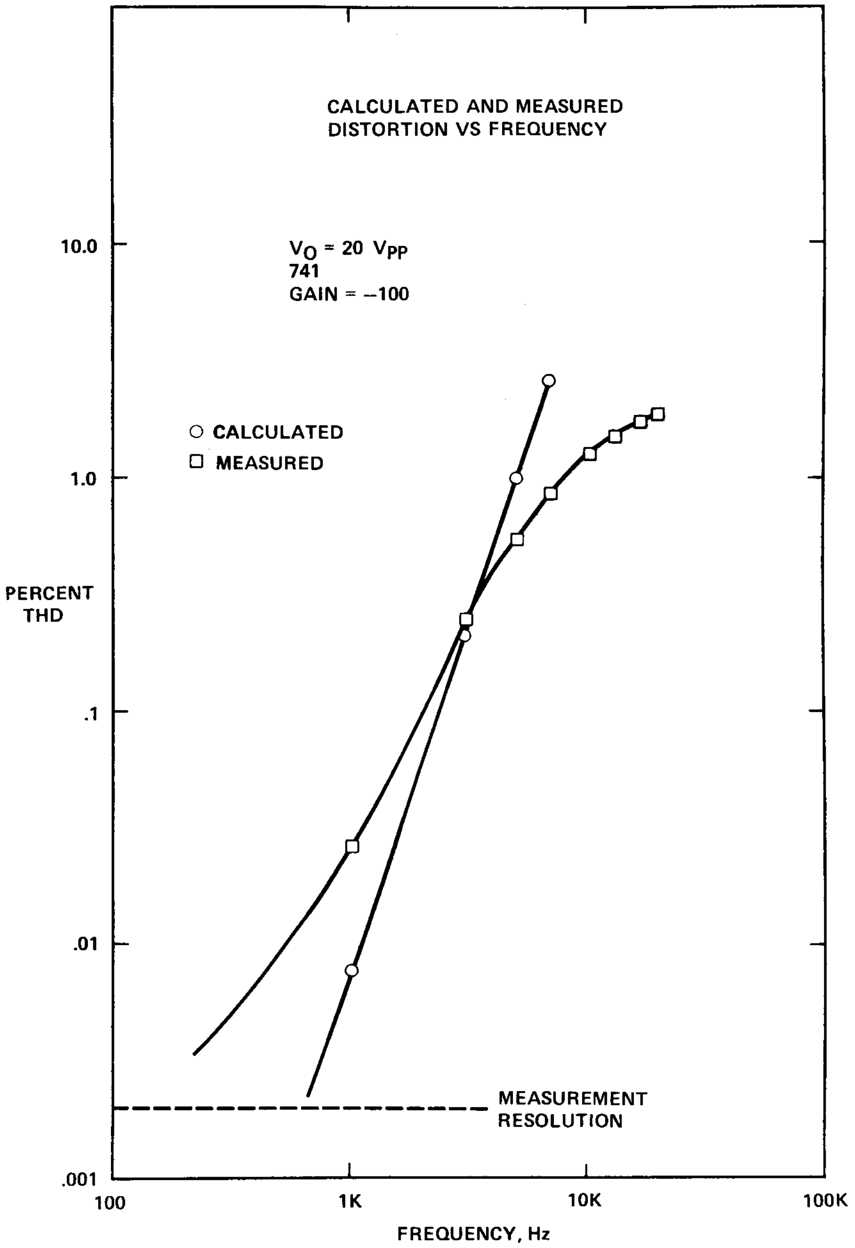


FIGURE 24

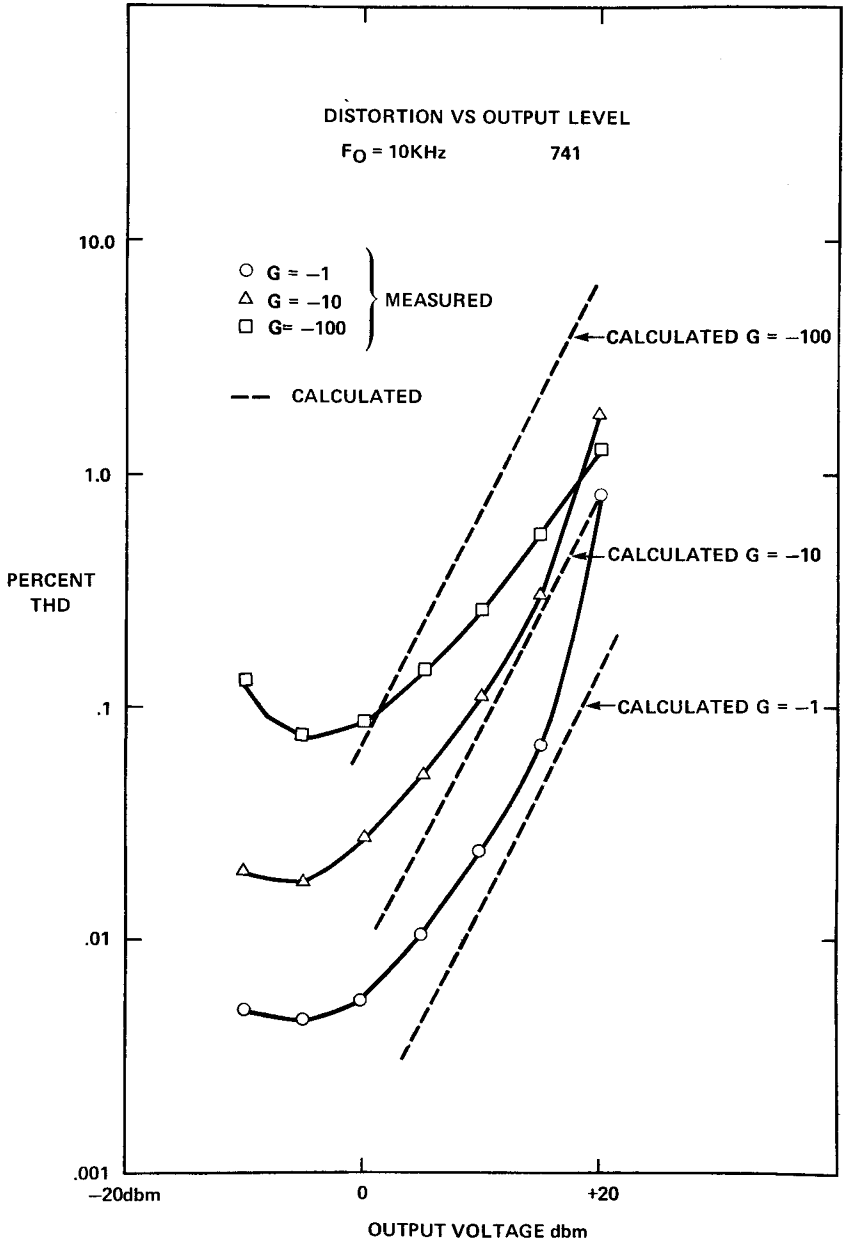


FIGURE 25

3) It shows that slew-induced distortion is increased by the sharpness of the non-linearity and decreased by higher gain-bandwidth products and larger feedback.
4) It demonstrates that since the slew rate of a constant amplitude sine wave is proportional to its frequency, that slew-induced distortion (or transient intermodulation distortion) should vary as the cube of the input slew rate. This is confirmed by the data in Figures 13 and 17, that show the variation of TIM with slew rate is a cubic relationship.
5) It indicates that since distortion can be predicted up to 85% of the intrinsic slew-rate limit of the device, that slew-induced distortion (or transient intermodulation distortion) is inextricably tied to the devices' slew limit. Those factors which cause signals to tax the slew capability of the amplifier, also increase distortion.
6) It shows that increasing a device's slew capability, without adding additional non-linearities, will reduce slew-induced and transient intermodulation distortion.

Present TIM theory suggests that feedback increases distortion. Our measurements and calculations show that, at least for signal conditions below the slew rate limit, that feedback reduces distortion. Actually the truth lies somewhere in between.

Increasing feedback reduces distortion provided the amplifier is operating below its slew-limit. For signal conditions above the slew rate limit, Figs. 22, 23, 24 show that more feedback will increase distortion. TIM measurements show this same pattern of feedback improving distortion below the slew limit and degrading it above the slew limit.

Listening Tests

These IC's were auditioned in a listening test to assess the degree of correlation between the various forms of electrical distortion and audible defects. These tests were done in mono, in an inverting configuration similar to Figure 2. To sensitize the test for SID however, the test device was preceeded by a preamp to drive it to near full scale output with program material. The output was then scaled down and level matched with the original input to within 0.2dB. A-B tests we then conducted on each IC to determine audible degradation.

The results of this test indicate that not only can SID be detected audibly, but that the ear is sensitive to very low levels of distortion. The results of these tests are summarized in Table 1, which also indicates the relative quality weighting.

"A" level quality is that indistinguishable from the source on the most difficult high frequency program material. In general devices of over 4V/µS slew rates fit into this category. Exceptions were some (but not all) slew enhanced devices, and the assymetric devices.

There are two broad categories of audible SID, one which can be associated with the approach of slew limiting, Category I; and one in which slew limiting actually occurs, Category II. The audible characteristic of the two are deterioration, and gross distortion, respectively.

Category II distortion will occur relatively infrequently on normal program material if the device slew rate is above 0.5V/uS. However, Category I distortion is possible in many instances and adjectives used to describe it have been seen in print often.

Design Guidelines

Some sensible design quidelines begin to emerge from this work. The primary one is speed-faster amplifiers are generally better. There are two

Table 1
Listening test results (referred to full output of ±10V)

Category of SID		I Deterioration		II Gross distortion	
Quality level	A	B	C	D	E
Audible character	No differences detected for any program material	Just discernible softening, loss of sweetness	Further softening, somewhat dry, generally satisfactory with slight loss of dimension	Colorations apparent, loss of dimension, "covered" sounds, dulled transients, constriction, edge begins	Coloration and distortion obvious, more constricted covered sound, transients smeared, grit edginess, fuzz
Associated slew rates	>4V/uS	2-4V/uS	1-2V/uS	0.5-1V/uS	<0.5V/uS
Samples Tested	318,518 TDA1034(5534) 2625 2525 8007 NE536 AD540 3140 TL084 OP-01 530A NE541(x100Comp) NE540(x100Comp) 531(x10Comp) 2720(5V/uS 301A(x10,x100,FP)	1456 530 NE541*(x10Comp) NE540*(x10Comp) 4136(2V/uS) 709(x10Comp)	1741S 356* 4741 535 538* 531(x1Comp) 2720(1.6V/uS) 4136(1V/uS)	741 2720(0.5V/uS) 301A(x1Comp)	2720(0.16V/uS) 709(x1Comp)

*Audible ranking possibly due to factors other than slew rate aspects to speed: bandwidth and slew rate. In general they tend to go up together. It can be confidently stated that raising an amplifier's GxBW, or ωu is desirable. The reason is that at any given frequency (neglecting D.C. and very low frequencies) the loop gain of the amplifier will be higher and more feedback related distortion reduction will take place, which lets one work closer to the slew rate limit.

It has also become apparent that higher slew rate is better, but some caution is required. Since slew rate is determined by the dynamic range of the non-linear input transconductance amplifier, it is important that high slew rate not be achieved at the expense of linearity. Some devices do achieve high slew rate at the expense of linearity. The slew-enhanced devices such as the 535 and the assymmetrically slewing 356 are examples of this. These devices are inherently incapable of performing as well as devices with more linear input stages. Emitter degeneration is an example of a technique that allows higher slew rate while at the same time linearizing the input stage. The 318 is a good example of this type of amplifier. FET input types are also excellent, provided they are symmetrical. A good example is the 536. For the same transconductance, FET input stages are linear over a much larger range than bipolar input stages.

To restate these design criteria, we primarily want an amplifier which is linear for large input signal (ΔV) levels. This gives us high slew rate and low open loop distortion. Secondly, we would like this amplifier to have as high a unity gain bandwidth (GxBW or ωu) as possible, so that when we apply feedback, the loop gain will be as high as possible for distortion reduction. The loop gain determines how close we can operate to slew limiting before

distortion begins to rise.

Some previously discussed design criteria for low TIM 3,4,7,9 such as the use of low feedback, low open loop (D.C.) gain, and a high open loop pole frequency (ωo) have no basis in fact or theory. More feedback increases the loop gain and reduces distortion. The location of the open loop pole (ωo) is of little significance to audio designers, and it does not have to be placed at a frequency above 20 KHz for superlative performance to be obtained. Our measurements support these statements.

From all of the above, it seems appropriate to adopt a new form of slew rate criteria for audio circuits. From the four series of tests (THD, IM, TIM, listening) this would be a criterion which specifies a minimum slew rate with regard to the maximum output voltage level in use. The criterion is:

> "The circuit, including all possible loading conditions, should posses a slew rate of 0.5V/µs (minimum) to 1V/µs (conservative) per peak output volt."

Application of this simple criteria will result in negligible SID, either electrically or audibly if the slew rate is symmetrical (± 20%) and the input stage has a smooth transfer characteristic (unlike the slew enhanced types.)

If large signals outside of the audio band are expected, it is wise to provide filtering to keep these signals out of the amplifier loop.[11] Otherwise these signals may cause the amplifier to approach its slew limit and generate SID.

Conclusions

One major result of this study is a much more clear assessment of the true behaviour pattern of operational amplifiers. Distortion has been analyzed qualitatively, quantitatively, and theoretically. This information can be applied by designers without the fear of violating arbitrarily contrived design rules relating to open loop D.C. gain or feedback factors.

Another major result is that tests for slew rate and SID are not only appropriate for audio gear, they are absolutely essential. Hopefully these terms will soon appear in both product specifications and test methods, rather than such terms as TIM, which are not only misunderstood, but technically incomplete and creating a great deal of confusion in the popular press[9,32,33,34] with but a rare example of understanding[31].

There is nothing "transient" about SID. It will occur continuously with steady high frequency tones. The fact that this distortion occurs in musical transients is due to the nature of the signal, and not the distortion mechanism.

As a final point, we feel there is still much to be learned about distortion mechanisms, measurement techniques, and perception. We consider this study but one step in that direction.

Acknowledgement:

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REFERENCES

TIM:

1)Daugherty, D.G.; Greiner, R.A. "Design Considerations for Linear Transistor Audio Power Amplifiers" Ph.D dissertation Univ. Wisconsin, 1964.

2)Daugherty, D.G.; Greiner, R.A. "Some Design Objectives for Audio Power Amplifiers" IEEE Transactions on Audio and Electroacoustics, Vol AU-14#1, March 1966.

3)Otala, M. "Transient Distortion in Transistorized Audio Power Amplifiers" IEEE Transactions on Audio and Electroacoustics, Vol AU-18 #3, September 1970.

4)Otala, M. "Circuit Design Modifications for Minimizing Transient Intermodulation Distortion in Audio Amplifiers" Journal of the AES, Vol. 20#5, June 1972.

5)Hamm, R.O. "Tubes vs. Transistors-is There An Audible Difference? "Journal of the AES, Vo.21#4. May 1973.

6)Stuart, J.R. "An Approach to Audio Amplifier Design", Parts, 1,2,3 Wireless World, Aug.-Sept.-Oct. 1973.

7)Lohstroh, J; Otala,M. "An Audio Power Amplifier for Ultimate Quality Requirements" IEEE Transactions on Audio and Electroacoustics, Vol AU-21 #6, Dec. 1973.

8)Otala, M;Ensomaa,R. "Transient Intermodulation Distortion in Commercial Audio Amplifiers" Journal of the AES, Vol 22 #4, May 1974.

9)Leach, W.M. "Transient IM Distortion" Audio, February 1975.

10)Leach, W.M. "Build a Low TIM Amplifier" Audio, Feb. 1976.

11)Leach, W.M. "Suppression of Slew Rate and Transient IM Distortions in Audio Power Amplifiers" AES preprint #1137, Fall Convention, 1976.

TEST METHODS:

12)Thomsen, C.;Møller, H. "Swept Electroacoustic Measurements of Harmonic Distortion, Difference-Frequency and Intermodulation Distortion" AES Preprint #1068, Fall Convention 1975.

13)Jung, W.G. "Let's Put Function Generators to the Test" Broadcast Engineering, Dec. 1975.

14)Jelsing, T. "Causes and Elimination of TID" AES Preprint #A-5, AES Zurich Convention, March 1976.

15)Holman, T. "New Factors in Phonograph Preamplifier Design" Journal of the AES, Vol. 24 #4, May 1976.

16)Leinonen, E; Otala,M; Curl, J. "Method for Measuring Transient Intermodulation Distortion (TIM) "AES preprint #1185, Fall Convention 1976.

OP AMPS:

17) Hearn, W.E. "Fast Slewing Monolithic Operational Amplifier" IEEE Journal of Solid State Circuits, Vol SC-6 #1, Feb. 1971.

18)Kesner, D. "A Simple Technique for Extending Op Amp Power Bandwidth" Motorola AN-459, May 1971.

19)Jung, W.G. "New IC Approach to Audio Power" Broadcast Engineering, October 1972.

20)Jung, W.G. "Optimizing IC Op Amp Speed" db, The Sound Engineering Magazine, January 1973.

21)Jung, W.G. "Improve Op Amp Audio Circuits" Electronic Design, Sept. 27, 1973.

22)Jung,W.G. "The Pitfalls of the General Purpose IC Operational Amplifier As Applied to Audio Signal Processing" Journal of the AES, Vol 21 #9, Nov. 1973.

23)Jung, W.G. "IC Op Amp Cookbook" Howard W. Sams & Co. 1974.

24)Jung, W.G. "Audio IC Op Amp Applications" Howard W. Sams & Co. 1975.

25)Jung, W.G. "IC Op Amps for Audio" Parts I, II The Audio Amateur, issues 2/73, 1/74, 2/74.

26)Solomon, J.E. "The Monolithic Op Amp: A Tutorial Study" IEEE Journal of Solid State Circuits, Vol SC-9 #6, Dec. 1974.

27)Otala, M; Leinonen, E., "The Theory of Transient Intermodulation Distortion." Monitor-Proc. IREE, Vol 37, March 1976, pp. 53-59.

28)Naryanan,S, "Transistor Distortion Analysis Using Volterra Series Representation," Bell System Technical Journal, Vol 46, pp. 991-1024, May/June, 1967.

29)Allen, P.E. "Slew Induced Distortion in Operational Amplifiers," IEEE J. Solid State Circuits, Vol SC-12, #1, Feb. 1977.

30)Sundqvist,B. "Transient Intermodulation In Amplifier's," Wireless World, Vol 83, No. 1494, pp. 37-39, Feb. 1977.

31)Cordell, R. "Another TIM View," Letters, Popular Electronics, Vol 10, #5, Pg. 6, Nov. 1976.

32)Klipsch, P. "High-Level Feedback & TIM," Letters, Popular Electronics, Vol 11, #2, Pg. 6, Feb. 1977.

33)Feldman, L. "New Trends in Hi-Fi Electronics," Popular Electronics, Vol 8, #6, Pg. 50, Dec. 1975.

34)Hodges, R. "The Great Tube/Transistor Controversy," Popular Electronics, Vol 10, #2, pp. 22-23, Aug. 1976.