Slewing Induced Distortion: Part 2a

Phase I: Total Harmonic Distortion Tests for SID

by Walt Jung
Contributing Editor

AT THE OUTSET of this study we really did not know what form of test methods we would need to completely identify, isolate and quantify slewing induced distortion (SID). Granted, it is readily observable on an oscilloscope (when gross), but to what degree will a percentage of "x" distortion be related to so many V/µS? Or will total harmonic distortion (THD) and intermodulation (IM) tests be shown to be related to slew rate? To each other?

Now that seems like a long time ago, actually. I have observed a pattern all through the course of my testing which correlates slew rate to measured THD in every instance where slewing is apparent. Hardly an isolated phenomenon, SID effects could be observed in all but one or two cases out of the several dozen IC types tested. Once I gained experience with the testing techniques, performance of devices which were tested late in the study could be reliably predicted from examining their specs.

As you will see when we get to phase II tests, a further correlation can be made between slew rate/THD tests and two tone 1/1HF IM tests. Once again, as I gained experience device performance could also be reliably predicted for IM tests, from either the THD results or the data sheet spec (if sufficiently detailed).

Although it's perhaps somewhat premature, I noticed in all cases that the THD tests seemed to stress an amplifier much more vigorously. I gathered similar data from both tests in relation to slew rate, but the THD tests were much more demanding of an amplifier. THD showed up faults more readily, and gave generally higher percentages of distortion. This is somewhat surprising, but probably most welcome to many, because the THD test method is so much simpler to use.

For the above reasons the bulk of the data I gathered in my study (and that presented here) is based on THD. It is clear to me that SID can be reliably detected by THD analysis, and that the results correlate well with other methods.

Block Diagram

The THD test system is relatively simple and consists of the equipment of Fig.I-1. There are two signal sources: a function generator supplying fast rise time square waves, and a low distortion sine wave source. The square wave source is used to observe the slew rate of the unit under test (U.U.T.), in conjunction with the oscilloscope.

The sine wave source provides the high purity sine wave for THD tests, and may or may not also contain the THD analyzer. Although in concept other gear could as well be used, the Sound Technology equipment conveniently supplies the required resolution, range, and accuracy in a single package.

Pertinent details of test set-up specs are as follows: the sine wave source and analyzer should have a residual distortion of ≈0.002% over the range of 100Hz to 10kHz, and as low as feasible up to 100kHz. The object is to make high resolution, extended range THD measurements at *full output voltage levels*, from 100Hz to 100kHz. The set-up must have extraneous or spuriously induced noise residuals of less than 100dB referred to full scale, for good repeatability and a high confidence factor.

The distortion products from the analyzer must also be made available for monitoring, by one channel of a dual trace scope, during THD tests. This enables the characteristic third harmonic distortion rise to be identified, pinpointing SID.

The square wave source should generate a variable frequency in the range of 1 to 100kHz, but will most often be used at 10kHz. It must produce ±10V square waves into a 50Ω termination with a rise and fall time of less than 100nS, preferably 50. The square wave should be free of overshoots, ringing or other fidelity shortcomings, as it will be used to measure devices under test. I used a Heath IG-1271 function generator, but many others are also satisfactory.

To begin a THD measurement on a device, we must first measure for slew rate using the square wave source and scope. Now at this point we must make quite clear what is done, and just how slew rate is measured in detail. Even if it seems simple, bear with me. We have pitfalls to avoid, as well as important subtleties to note.

First of all, a measurement of slew rate must be just that, a measurement of the amplifier's output in a *slew limited operating mode*. At low output levels the output waveform from an amplifier should resemble Fig.I-2a, which shows exponential rise and fall (characteristics of an RC time constant). In the low signal level range (1-2V) this shape will be observed, but as we approach full output, the output waveform will taken on a linear rise and fall time, with ramplike slopes, as in Fig.I-2b.

This slew rate limited condition is best measured at full rated voltage swing; for standard op amps this equals ±10V. The peak amplitude swings must not be allowed to clip, as this may invalidate the reading(s). If there is any doubt whatsoever concerning possible clipping (clipping of a square wave is not always obvious), switch the function generator momentarily to triangle or sine, waveforms with peaks which will readily display clipping.

Now to be accurate in measurements, the scope (plus probe, if used) must be a wideband model, with less than 50nS risetime and 10mHz or more of bandwidth. It must also have an accurately calibrated time base (as well as vertical deflection), since slew rate is being measured as voltage change per unit of time.

In the course of testing op amps, many different slewing waveforms will be noted. The waveform of Fig.I-2b is ideal and is drawn here for reference (if you find one, let me know). Note that both the up (+) and down (-) ramps of the waveform are smooth, constant slopes and precisely symmetrical. There are no aberrations such as overshoots or ringing.

In practice you more often see waveforms such as Figs.I-2c, I-2d, and I-2e. There are all undesirable for various reasons. Exactly why is covered below under the discussion of various devices.

In making a slew rate measurement,

FIG. I-1

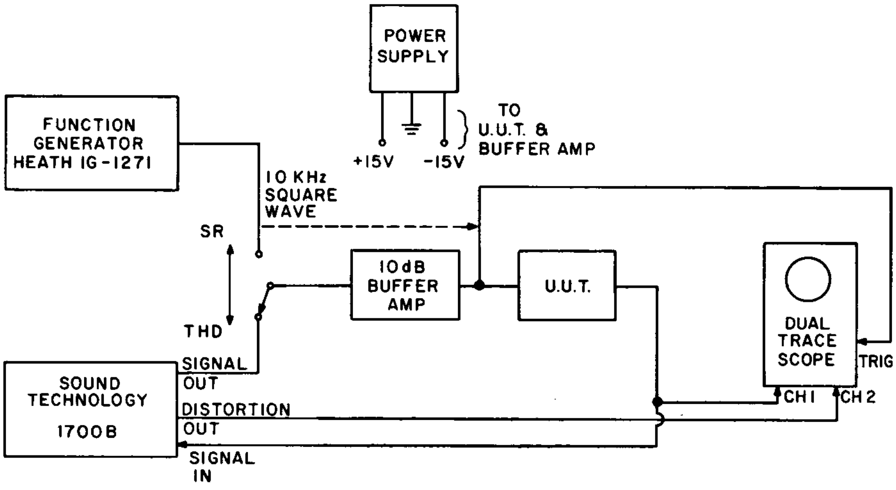
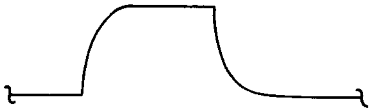
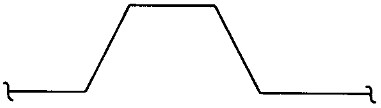


Fig.I-1: Block diagram, THD test setup.

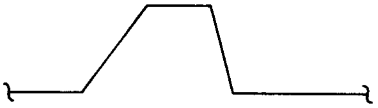
FIG. I-2



a:
EXPONENTIAL RISETIME-BANDWIDTH LIMITED

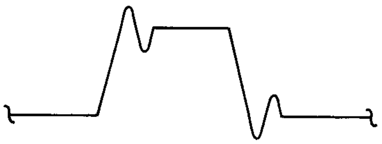


b:
LINEAR, RAMPLIKE RISETIME-SLEW RATE LIMITED (IDEAL CASE ILLUSTRATED)



c:
ASYMMETRICAL SLEWING

d:
NON UNIFORM SLOPE(S)



e:
OVERSHOOTS

Fig.I-2: Visual waveform differences, and aberrations.

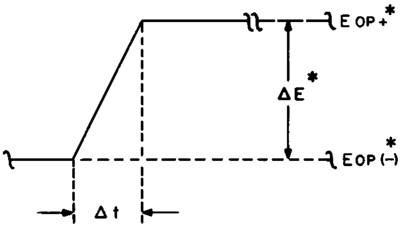
carefully adjust the starting position of the waveform so that the beginning of the slewing interval is aligned with the left graticule marker (see Fig.I-3a). Then adjust the signal level until the vertical deflection is exactly 20V p-p. Slow down the time base to ensure you measure the 20V between the *flat* portion of the square wave, and not any peaks, dips, or other bumps which can occur near the (+) (-) transitions.

With the waveform adjusted in amplitude for the exact rated output, then again speed up the time base for a convenient display of the slewing ramp (for instance, 1μS/div) and recheck the beginning of the slew interval for the horizontal calibration point. Then read the slewing time interval, Δt, as the time from slew beginning to the crossing of the peak voltage.

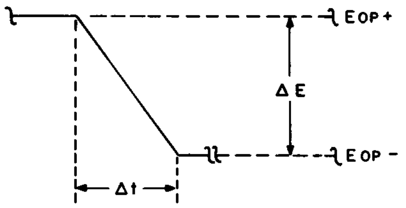
You may have some difficulty if there are overshoots or other distortions. In these cases extrapolate the end point of the slew rate to where it would first cross the peak deflection. This may be necessary at either the beginning or end of the slew interval.

Measure both (+) and (-) slew rates (which may well be different) and note their rates in V/μS. Two examples are shown in Figs.I-3a and I-3b; in cases where they are different, note this accordingly.

FIG. I-3



a:
POSITIVE SLEW



b:
NEGATIVE SLEW

$*\Delta E = Eop^{+} - Eop^{-}$

$SR = \frac{\Delta E}{\Delta t}$

Example: $Eop^{+} = +10V$
$Eop^{-} = -10V$
$\Delta t = 10\mu S$
$SR = \frac{10V-(-10V)}{10\mu S}$
$= \frac{20V}{10\mu S} = 2V/\mu S$

Since Δt is measured from Eop^{-} to Eop^{+}, this is positive slew, then
$SR(+) = 2V/\mu S$

For negative slew, use same basic expressions, but label accordingly.
Example: $\Delta V = 20V$, $\Delta t = 15\mu S$
$SR(-) = \frac{20V}{15\mu S} = 1.3V/\mu S$

Fig.I-3: Measuring slew rate.

The unity gain test circuit of Fig. I-4 was used in all but a few cases for measuring slew rate. Slew rate is measured with Rx open, in a unity gain inverting mode with x1 (unity gain) compensation for the device being tested (if an externally compensated unit).

Thus, the slew rate given with a device's data is the actually *measured* (not data sheet) slew rate. Supply voltages are ±15V within 0.1%, unless otherwise noted. Special cases of compensation are noted on the data which follow, as well as corresponding slew rates.

From the block diagram (Fig.1) you can observe that the drive to the U.U.T. comes through the buffer amp. Normally this creates no problem in measuring slew rate, as the 318 is one of the fastest slewing devices available (over 60V/μS on the unit used) and will thus create little additional error if the slew rate of the U.U.T. is less than 15 or 20V/μS. In the case of a high speed device (>20V/μS), the square wave can be applied directly to the U.U.T. at a ±10V level (shown dotted).

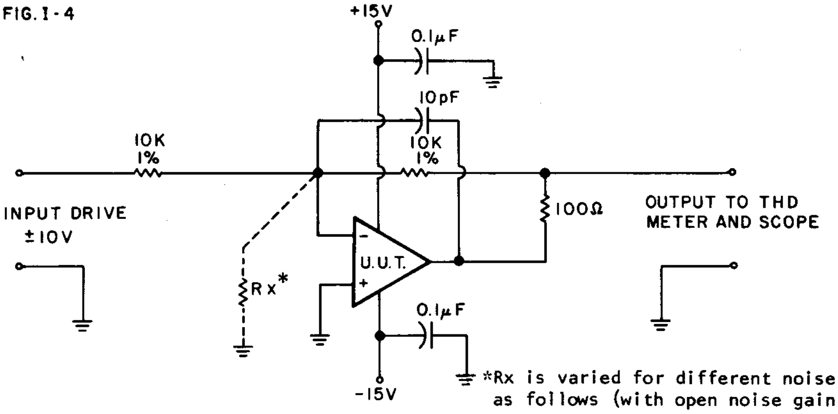
The buffer amplifier, shown in Fig.I-5, is necessary to elevate the output level of the Sound Technology 1700B up to ±10V so as to be capable of driving unity gain op amp circuits to full output. Its 10dB gain gives some reserve output capability beyond ±10V (or 7V RMS).

The A1 device is of critical importance, as any THD or noise generated in this stage will be seen as an ultimate resolution limit, if greater than that of the Sound Technology. The device used here must outperform all others being tested.

Fig.I-6 illustrates the performance of the 318 device used for the buffer amp in all tests. The lower curve here is the basic residual THD of my 1700B, from 100Hz to 100kHz. The rise in THD above 30kHz is due to SID in the 1700B's oscillator, by the way.

A 318 used in the buffer essentially duplicates this curve, but with slightly higher THD readings, due mostly to the *noise* of the device, not actual distortion. The 318 actually has less distortion than the oscillator, but since they cannot be separated, the composite curve becomes the new reference residual distortion level. The 518 was also evaluated in this circuit and yielded results comparable to the 318 in terms of speed and low distortion, but with slightly higher noise, as reflected in its curve. Either device is usable for the buffer function, but the 318 is preferred for its lower noise floor and thus greater potential resolution.

FIG. I-4



*Rx is varied for different noise gains as follows (with open noise gain is 2).

Noise Gain	Rx
3	10K
5	3.3K
12	1K
102	100Ω
1000	10Ω

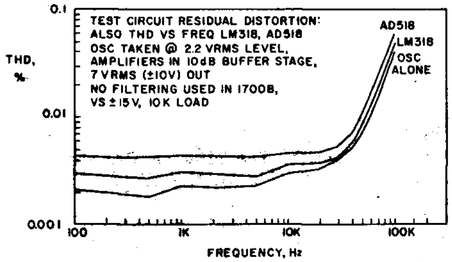
Fig.I-4: Test circuit for slew induced distortion.

As noted in the conditions, I used no filtering in the THD measurements, due to the 100kHz range. Quite often wideband noise limited the ultimate accuracy of THD measurements at low frequencies, but for the sake of consistency all measurements are wideband, even in view of this apparent sacrifice. Ultimate THD below 1kHz is hardly likely to be SID, so this is not a serious compromise.

The importance to SID detection of the extended range (1kHz through 100kHz) cannot be over-emphasized. This measurement *must* be done to lend any validity to conclusions. Single frequency spot THD measurements, which have been reported as "uncorrelated," are a gross oversight at best, and are simply not comprehensible as an objective analysis. The goal is to paint a picture of rate-sensitive distortion, and extended range THD is the means.

As you can note from the Fig.I-4 U.U.T. test circuit, we use the inverting mode at unity gain unless otherwise specified, and at the device's full rated (±10V) output. The use of inverting mode eliminates contamination of measurements due to common mode distortion which appears in the non-inverting connection. The unity gain compensation gives the worst possible case for slew rate, the one most likely to generate SID.

FIG. I-6



One might argue that the high feedback of the unity gain connection can mask the level of SID, but in practice this is not the case. As it turns out, if slewing distortion is present it becomes woefully apparent without great efforts at detection. In certain cases, higher stage gains are set up by reducing the feedback around the U.U.T. by means of Rx. Noise gains higher than that of two for the standard case are illustrated in the table.

Test circuit input and feedback resistors are 10k, to minimize the loading of both the buffer and the U.U.T. If additional distortion were to be generated due to U.U.T. output stage non-linearity or loading effects, it would be difficult to separate from SID. Thus minimal loading is used, to maximize sensitivity to SID (only) detection.

I am certainly aware that both the inverting-only connection and the minimal loading stipulations for this test are somewhat unrealistic, in a practical sense. However, as the two forms of distortion which we eliminate by these are to be covered in a separate study, I believe these procedures are much more definitive in isolating SID. Indeed, to test otherwise it would be difficult (if not impossible) to positively identify the distortion source(s).

FIG. I-5

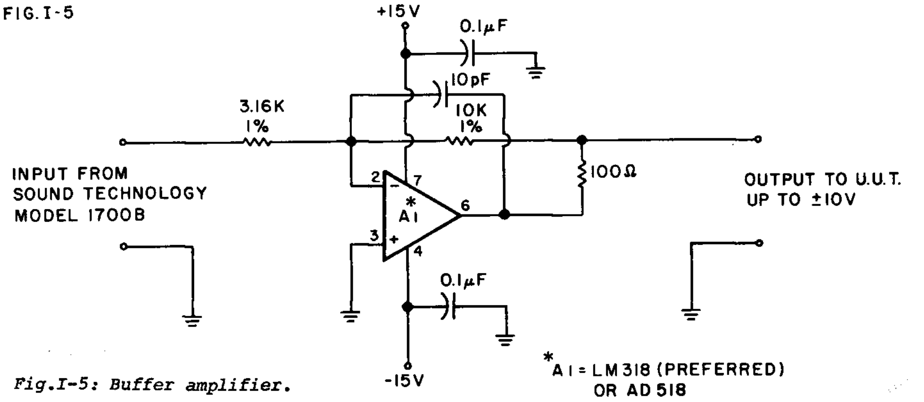


Fig.I-5: Buffer amplifier.

Test Results

A good way to begin discussing test results is to examine slew induced THD at various levels in a popular IC type (the 741). See Fig.I-7.

Since slew rate is a measure of the output rate of change, it follows that either frequency or peak amplitude can be used as the variable (with the other held constant) to examine its nature. Fig.I-7 shows the peak amplitude and frequency relationship and the resultant THD, for a 0.5V/µS slew rate device.

As might be expected, the 7V RMS (or ±10V) output level curve shows the worst distortion, as it occurs lowest in frequency. At lower levels of 2V and 1V RMS the distortion curve retains the same general shape, but is pushed upward in frequency. This curve shape is a classic one, and also one which we can immediately recognize as resulting from SID. It will recur repeatedly throughout this study, for almost every device examined.

The curves are so similar in shape that you can predict the 1% THD intercept point from the ratio of amplitudes, almost exactly. For instance, the 7V RMS curve crosses at 8kHz, the 2V RMS curve at 25kHz. These ratios (7/2 and 25/8) are nearly the same. This also holds true for the 2V and 1V RMS curves, as well as many others, as we will see in due course.

It might be argued that reducing the output level of a low slew rate device (such as the 741) will allow it to be used in audio circuits, such as for example the 1V RMS curve (a typical line level). However, the device can still generate serious distortion on signal peaks at high frequencies, as is evident by the 2V curve and will be further demonstrated by the IM tests. Bear in mind also that this is a unity gain condition: higher gain (more practical) circuits blacken the picture much more severely.

Fig.I-8 shows the variability of slew rate and resultant THD for samples from three different 741 vendors. The slew rates are 0.5, 0.8, and 1V/µS; the resulting curves are similar to those of Fig.I-7 in general, although in this case all are taken at ±10V out. We must expect such variability in IC op amps.

A dramatic demonstration of how SID can limit audio frequency performance is contained in the data of Fig.I-9. These curves represent measured performance of the 0.5V/µS slew rate 741 sample, which is a device close to the "typical" slew rate spec. These data demonstrate just how such a device would perform in typical higher gain circuitry.

The lower of the three curves (#1) shows the same data as contained in Fig. I-7 (for 7V RMS), repeated here for reference. The second curve is for a noise gain of 12, while the third curve is for a noise gain of 102.

While curve #1 is certainly poor performance if considered alone, it is "good," relatively speaking. The op amp feedback mechanism here is attempting to reduce the strong third harmonic being generated due to slewing. Curve ##2 and 3, which are taken with progressively less feedback, therefore show much higher distortion, due to less correction. These two curves, particularly #3, show performance which can hardly be considered adequate for any audio use of reasonable quality.

Note the data are only plotted up to 8kHz; distortion would be even worse above 10kHz. Curve #3 appears to indicate a decrease in distortion above 5kHz. This is misleading, since the distortion is still being generated, but the harmonic product percentage is reduced by the rolloff of the amplifier, due to its 3dB bandwidth of 10kHz for this feedback condition. In reality distortion is even worse than is evident here.

While this example is rather gross in terms of performance, it is not at all uncommon to see 741 (or comparable slew rate capability devices) specified for audio use. This should only be done if the output signal levels are maintained to *very* small peak levels perhaps a factor of 10 (or more) below the conditions of Fig.I-9 and if the required bandwidth(s) are narrow and/or the gains low (high feedback factors).

FIG. I-7

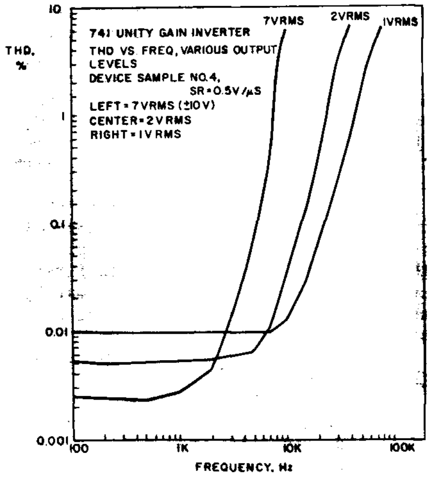
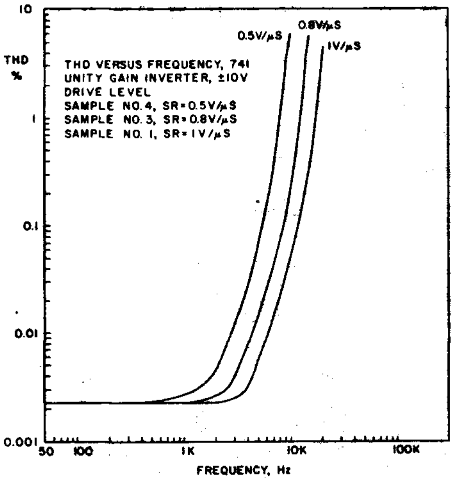


FIG. I-8



In short, it would be much safer (and wiser) to relegate the 741 and other low slew rate (<1V/µS) devices to voice grade and other low accuracy, poor fidelity applications where its shortcomings are less of a hazard, and true op amp predictability is not a prerequisite.

One method of improving an op amp's slewing capability (and consequently its final distortion parameters) is to *custom compensate* it for the exact working gain to be used. As should be painfully obvious, not only does a low slew rate in an internally compensated unit create large distortions at low gains, the situation becomes progressively worse at higher stage gains, as shown by the 741 example.

It may come as a surprise to some, but slewing rate restrictions in an amplifier compensated for unity gain conditions can be such an overriding limitation that in many cases the net situation can be improved by operating at a *higher* gain (and higher slew rate), with *less* overall feedback. This fact is demonstrated using three different IC amplifiers as examples, beginning with Fig.I-10. The data derived from extended range THD tests on these amplifiers also illustrate several other factors of distortion performance. The implications are highly inportant for drawing correct conclusions in a given situation as to the nature of distortion observed.

The first example is the 709, a notoriously slow amplifier with unity gain compensation, as its slew rate is only 0.2V/ S. This is even slower than a 741, and the 0.2V/µS (x1 comp.) curve (A) of Fig.I-10 demonstrates just how severe the slew induced distortion is at only a few kHz. However, being an externally compensated unit, the 709 can be adjusted for optimum compensation, that is, compensation to match the actual working gain.

With x10 compensation, curve B, the device slews at about 2V/µS, and the beginning of the almost vertical slope of this curve (which indicates severe SID) is pushed out to about 20kHz. Note the absence of an obvious rise in low frequency distortion, as the real LF distortion below 1kHz is masked by noise. This curve's slope from 1kHz to 20kHz is more gradual, compared to the slew limited area above. In this region the feedback loop is attempting to correct other distortions in the device, most of which is the crossover distortion due to its class B output stage. The gentle upward slope is due to the open loop bandwidth rolloff of the 709.

Curve C, x100 compensation and noise gain, illustrates performance which is not dominated by slew limiting at all, but reflects further the open loop bandwidth rolloff, and higher rise in distortion due to progressively less feedback.

My point is that although the feedback has been reduced by a factor of 100 from the first to third curves, we see no corresponding x100 increase in distortion. To the contrary, distortion is actually reduced due to slewing improvements over most of the range, and at low frequencies where slewing is not a factor, rise is less than a factor of three-to-one in degradation.

An amplifier such as the 709, if skillfully applied, can be an effective performer due to its excellent maintenance of gain-bandwidth with differing compensations. Unfortunately, the 709's class B output stage generates quite a bit of crossover distortion, particularly at high frequencies, and this can be one of its ultimate limitations. Newer devices free of this defect can be more effective.

The 301A can also be custom compensated, and in some ways is more attractive, as it only requires a single compensation capacitor where the 709 needs three components. You can go only so far with "opening up" the bandwidth, however, because the unity gain capacitor is only 30pF. Generally speaking, the larger this capacitor, the more you can do with it by way of reducing its value, thus increasing bandwidths and slew rate.

FIG. I-9

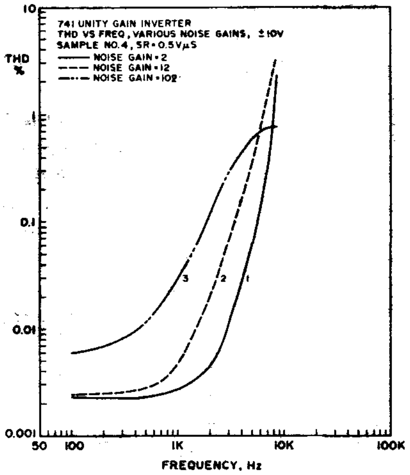


FIG. I-10

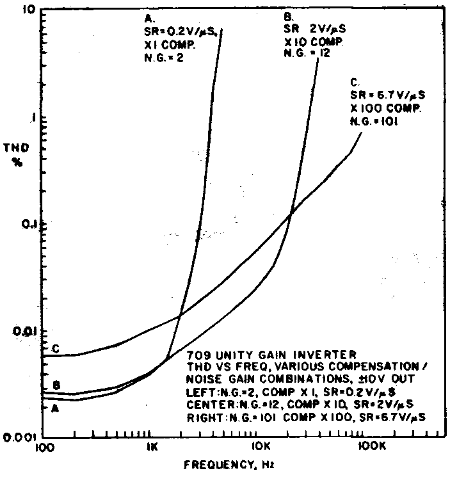
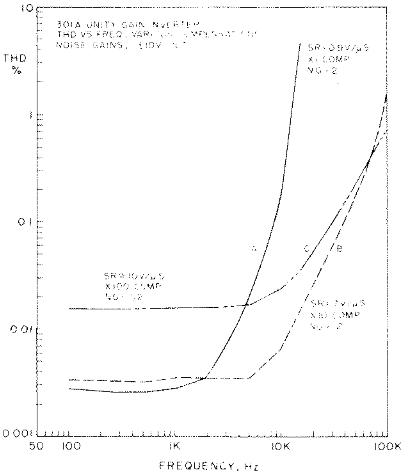


FIG I-11



With the 301A sample plotted in Fig.I-11, the unity gain slew rate was 0.9V/µS, which shows the characteristic slew rate limited rise beginning at a few kHz. With x10 compensation, curve B, this effect is pushed upward in frequency where it shows similar shape, the 7V/µS curve. Note the low frequency distortion is still quite low, and there is no rise at middle frequencies as with the 709. Curve C, x100 compensation, is not a stock trick for the 301A; it was done in this case by using a 1pF or so twisted hookup wire "gimmick" (four turns of insulated #22 about ½" long) wired between pins 1 and 8. Also, pin 5 of the IC must be snipped off at the body to reduce its positive feedback, which will otherwise limit stability.

These data show somewhat higher distortion at low frequencies (actually noise) but without gross slew limiting, just a bandwidth rolloff increase in distortion. It is apparently greater than 6dB/octave at HF, due to lack of feedback to suppress the remaining slew induced distortion. For this device, both the x10 and x100 compensation performance are reasonable for modest accuracy applications, certainly a far cry from a 741 or 709!

The NE540 power driver amp excels at high gains because of an inherently high slew rate and bandwidth. (Don't confuse it with the *AD540*, a different device I discuss later.) This unit is an excellent example of an IC with good audio characteristics, and also aptly illustrates the effectiveness of custom compensation. See Fig.I-12.

Compensated for a x10 gain, the NE540 has a slew rate of 4V/µS. Its performance for this condition is not too spectacular (but not totally unreasonable either) and it becomes slew limited at 40kHz. For the x100 compensation, however, the slew rate is more than 20V/µS and, as the curve shows, there is no slew limiting whatsoever, just a bandwidth rolloff related distortion rise above 10kHz. The NE540 can also operate *uncompensated*, at a gain of 60dB. At this level distortion is of course easily measurable, about 0.15% below 10kHz. Still, this is very respectable performance in view of the high gain, and the device will slew at 100V/µS for this connection.

To give further insight and understanding of the interaction of slewing and gain rolloff related distortion, Fig.I-13 is an open loop plot of the NE-540's gain and THD. At low frequencies, the open loop gain is 93dB, and the open loop bandwidth is slightly more than 10kHz. Open loop distortion is quite flat, at about 3.3%. Above 5kHz gain rolloff invalidates measurements.

If we compare these findings to those in Fig.I-12, the bandwidth rolloff at 10kHz in Fig.I-13 corresponds to the upturn in THD at the same frequency, in Fig.I-12's gain of 1000 curve. Further, the distortion measures 0.15% which is a ratio of 22 with regard to the open loop distortion of 3.3%. With feedback, the NE540's open loop gain drops 6dB (to 87dB), due to the loading effect of the 10K feedback resistor on the device's open loop 10K output impedance. Thus the actual feedback is 87 - 60dB, or 27dB, a ratio which is almost exactly equal to the measured distortion reduction.

This point may seem belabored to some, but I stress it here because in so many instances you *cannot* predict closed loop distortion as readily, as for instance in the gross effects caused by slew limiting, which can confuse the issue to the point of frustration.

From this information you could also extrapolate the true THD at low gains; at the x100 compensation the measured 0.015% also agrees well. The x10 compensation does not precisely agree, as it predicts a distortion of 0.0018% and 0.003% was measured. The minor difference is due to noise and measurement resolution limitations.

An effective distortion reduction technique with an amplifier whose bandwidth can be "opened up" (such as the NE540) is what is popularly called "input compensation." This is nothing more than an RC network across the amplifier input terminals which forces the feedback loop to a high gain level, *at high frequencies only*. It does *not* (as some authors have implied) "roll off" the input signal, as the network is applied differentially, between the (+) and (-) terminals.

In simple terms, this technique allows a very high loop gain at low frequencies, and a correspondingly high slew rate. The slew rate is, in fact, one which would accompany the compensation appropriate for gain level of the network, such as 40dB.

To illustrate the effectiveness of this technique, I applied input compensation to the NE540 (with values chosen as outlined in my *IC Op Amp Cookbook*,[24] p.285). This is a x100 stage insofar as compensation goes, but *unity gain* for signals. Therefore at low frequencies almost the full open loop gain is available for feedback (minus only 6dB). Here the feedback would be 81dB, thus the distortion should be 0.0003% or 3ppM (parts per million). It measures a great deal higher, of course, due to the noise components generated by the large HF gain. Much of this noise is out of band, however, and therefore not audible (although measurable). If you examine the distortion curve for this operation you can see that it curves upward above 10k, the point where the feedback is diminishing, thus allowing distortion to rise.

FIG. I-12

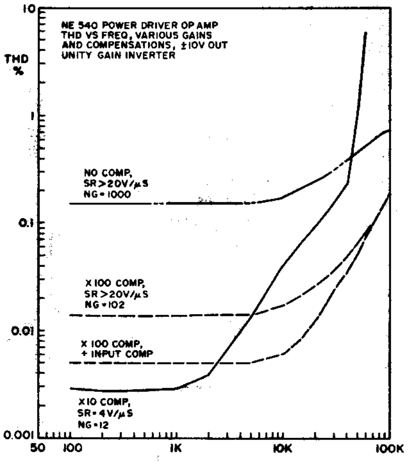


FIG. I-13

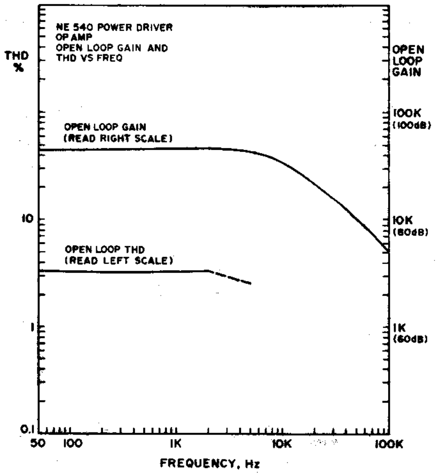
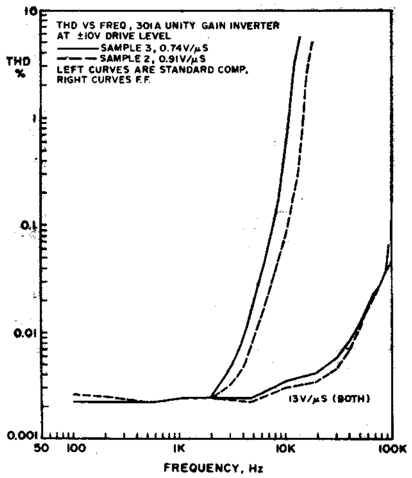


FIG. I-14



Input compensation is applicable to (and effective with) any adjustable compensation amplifier which can (or must be) compensated for high noise gains. This includes the devices just discussed as well as many others, and also some of the newer "decompensated" op amps. A decompensated op amp is simply one which is stable at some minimum gain *higher* than unity, such as x3, x5, x10, etc. Several examples of this type of op amp are shown in the data which follow, and they are generally capable of much higher slew rates.

FIG. I-15a

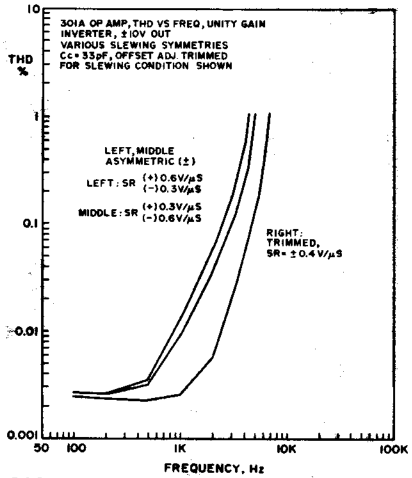
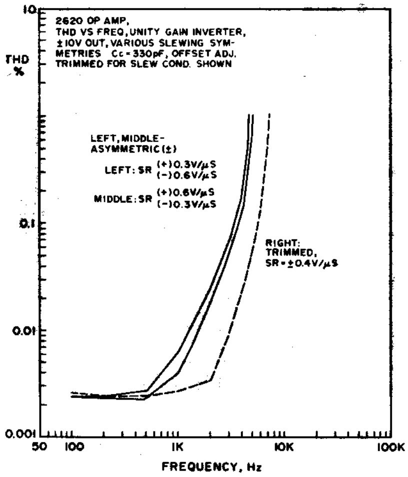


FIG. I-15b



As we saw with the 741 data, the range of slew rate variability is fairly wide (as is the consequent audio performance) among products of various manufacturers of a given device. Even a specific manufacturer's device will have tolerance variations in a single lot and more substantial variations between different "runs."

For the 301A, as compensated for unity gain, the vendor-to-vendor variation is illustrated by Fig.I-14. The two samples have slew rates of 0.7V/µS and 0.9V/µS. Again this generates the characteristic slew limited distortion curve, slightly separated due to these differences in slew rate.

However, the 301A is unique in that it can also be operated in a *feedforward* mode, in inverting (only) applications. This type of operation yields a much higher slew rate, specified as 10V/µS. The devices tested here both had slew rates (in the feedforward mode) of 13V/µS. This is sufficient to allow truly exceptional performance, as the THD is very low, being only slightly in excess of the source residual.

This class of performance is what we should all be seeking for high quality audio circuits. Use of the 301A for this operation is particularly attractive because of the circuit simplicity, and of course the unit's basic economy. It is highly suitable to summers, mixers, buf-

FIG I-16

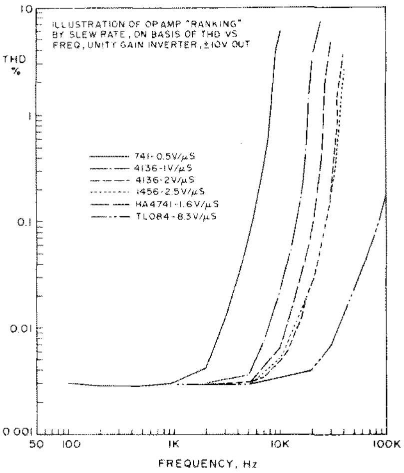


FIG I-17a

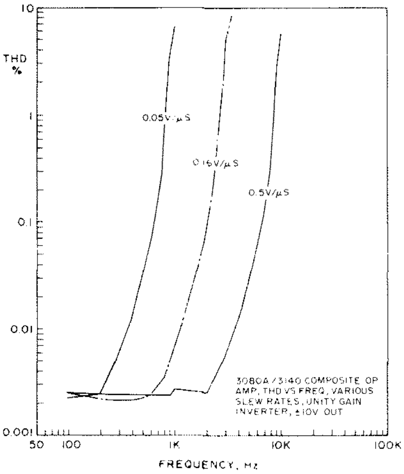
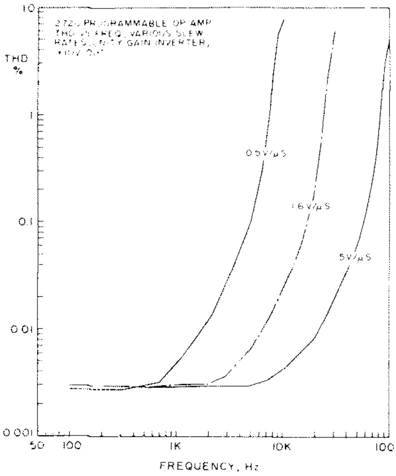


FIG I-17b



fers, multiple feedback filters, and other inverting type audio circuits.

The 301A serves well to demonstrate another aspect of the slewing induced distortion problem, in Fig.I-15. The degree of slewing distortion generated in a given op amp is closely related to the *symmetry* of the positive and negative slewing rates. Ideally, they should be as nearly identical as possible, to produce predictable results. Usually, most IC op amps are fairly good in this regard, but we cannot assume it to be a general rule for two reasons. First, manufacturers rarely specify slewing rate as more than a typical parameter, and they never specify it for symmetry. So you really have no control over it whatsoever, other than your own knowledge of a given manufacturer's product.

Should a device have a basic "built-in" asymmetry, it will never yield as low a distortion as even a slower device which possesses good symmetry. One prime example of this is the 356 op amp which slews with a 2/1 asymmetry (which can also vary). Although it is a reasonably fast device with a slew rate of 15V/µS, it is easily bettered by several slower devices (as will be shown).

To demonstrate the sensitivity to slew rate symmetry, I set up a 301A in a x1 compensated test circuit, but with a variable DC bias current injected into the input stage's current mirror, pins 1 and 5. It has been generally observed that op amps which employ a current mirror in the first-to-second stage interface (see Issue #1, 1977 series, p.6, Fig.E) can often be *trimmed* for slew rate, by altering the static DC bias in the current mirror sides.

If slewing is to be completely symmetrical the current gain of the mirror stage should be unity, so as to deliver equal charge and discharge currents to the compensation capacitor. With the 301A, for instance, the slew rate can not only be trimmed to a nominal (+) and (-) match, but symmetry can also be altered to a range of 2/1 or 1/2 (or even more).

Fig.I-15a shows the result of this in terms of THD. Note that the two asymmetrical slewing cases show a much higher distortion than the symmetrical case; at 2kHz, for instance, the difference is as much as an order of magnitude. Also the distortion breaks away from the residual noise level at a much lower frequency for asymmetrical slewing.

A similar test on a completely different op amp shows results which are remarkably similar. In Fig.I-15b a 2620 was compensated with a relatively high capacitance (330pF) to yield a basic slew rate identical to the 301A case, and symmetric/asymmetric data taken. The general character of performance is virtually identical to the 301A.

With either of these devices (and others which show this (±) slew trim capability) a distinct dip can be observed in THD as the slew rate is trimmed for symmetry. Generally, this can be accomplished via the device's offset trim network, but there may in some cases be minor differences. Note, however, that this method of trimming slew rate will not necessarily result in lowest DC offset; in fact, it will most likely *compromise* the DC offset.

Why the slew rate needs to be symmetrical for lowest distortion may be intuitively appreciated if the overall feedback loop is considered for signals in the slewing region. If slew rate is asymmetrical, the feedback loop (in attempting to maintain a constant output voltage) will force the input stage into an unequal (+) and (-) deviation from balance. An asymmetric slew rate may also be viewed as unequal positive and negative going gains, which result in unbalance. If we monitor the summing point with an oscilloscope during asymmetric slewing we can see that the error voltage will have a parabolic waveshape.

Asymmetric slewing produces even order harmonic distortion, whereas symmetric slewing produces odd harmonic products. Watch the distortion products during slew trim and you'll see the even order ones go to minimum as slewing becomes symmetrical. Symmetric slewing optimizes utilization of the input stage's transconductance curve, so as to generate the least objectionable (non-zero, but minimum) combination of distortion products as a result of slewing conditions.

Although slew trimming of an amplifier is impractical for general use, the point is the sensitivity of this parameter to symmetry. In evaluating an amplifier, pay close attention to the symmetry of the slewing, as well as the basic rate. This caution applies to *all* audio amplifiers (not just op amps) and the testing of this parameter should be a standard procedure for audio circuit evaluation.

It may have already occurred to the reader that, using these insights, amplifiers could be *ranked* according to their slew rates. To some extent this is true, but it is not a completely all-inclusive statement, due to other factors.

Generally, if the slew rate being considered is 2V/µS or less the statement about ranking is true. In this range, bandwidth is not a great factor at all, as demonstrated by Fig.I-16.

The first four curves here are for different devices, and their major separating factor is slew rate. The 0.5V/µS 741 curve is for reference; following this are a 1V/µS 4136 curve, a 1.6V/µS HA4741 curve (not to be confused with the MC4741), and a 2V/µS 4136. Clearly these devices at least can be ranked by slew rate alone as far as performance is concerned.

The 4136 samples are an interesting point; the 1V/µS unit is an original source unit (an RC4136) selected for a close-to-spec. slew rate. The 2V/µS unit is an XR4136, a second source improved 4136, a design which features significantly higher slew rates. The HA4741's spec. is 1.6V/µS so it is right on the money, as being typical. This is, incidentally, the same spec as the XR4136.

Another method of demonstrating how slew rate can completely dominate the distortion characteristic of an op amp is to generate a *family* of curves which show varying degrees of distortion versus frequency, for various slew rates using a single device, with fixed unity gain compensation. This effect is shown in Fig.I-17, actually the same sort of information for two different op amps, which have different slew rate capabilities, but can be made to overlap. The two devices chosen are programmable op amps, a device operational feature which allows slew rate to be selected by appropriate bias, and a family of THD vs. frequency curves generated (for each device). Input stages of both devices are undegenerated bipolar types.

Fig.I-17a shows three distortion curves for a 3080, set up for slew rates of 0.05, 0.15, and 0.5V/µS, respectively. For this test I selected a 3080A device from several for symmetrical slew rate, and used a 3140 unity gain follower to buffer the high impedance output node of the 3080A. (For details see my *IC Op Amp Cookbook*,[24] p.448.)

Interestingly enough, these three curves are, to all intents and purposes, *identical* in character, and are also precisely separated in frequency by the ratio of slew rates chosen, 10dB in this case. Since the 3080 is a linearly programmable device, one can generate an infinite number of these curves for it. Thus within the bounds of device performance, the designer may choose his limiting THD curve by adjusting slew rate.

The 2720 operates similarly but has a decade greater slew rate capability. Fig.I-17b traces its performance for adjusted slew rates of 0.5, 1.6, and 5V/µS. The curves are very similar to those of the 3080A, and they also occur at 10dB frequency separations, again in direct proportion to the slew rate(s). The two 0.5V/µS curves in I-17a and I-17b are decidedly similar, though measured from two different devices. Data from these two amplifiers for these conditions show that slew rate is the primary determining factor in producing distortion. It also indicates that only when a device has a slew rate of several V/µS does THD become very low (≤0.01%) across the whole audio bandwidth. The inescapable conclusion: slew rate is one of the major criteria of device performance for audio applications.

We may now assume that if slew rate is sufficiently high, distortion will be negligibly low, but this reasoning does not apply in every case. Fig.I-18 demonstrates that we must qualify a general statement of this nature in terms of specific device characteristics, as there are exceptions where distortion performance cannot be totally predicted from specified slew rate.

These data show similarly based distortion performance for "slew enhanced" op amps, typified by the 531, 1741S, 535, and 538. Such slew enhanced op amps utilize a class B input stage to dynamically increase the charging current of the amplifier's compensation capacitance. While this technique prevents total slew limiting and the resulting several percent distortion, it is not a panacea for low audio distortion. The class B mechanism, however, is only active at relatively high input levels; thus the *low level* SID of a slew enhanced op amp will be quite similar to an unenhanced device with a comparable (unboosted) slew rate.

You can observe this factor first in the data for the 531, which exhibit an initial distortion rise as the onset of complete slew limiting is approached. The device plotted here, for instance, appears to be similar to a conventional 1V/µS device in the shape of its initial distortion rise, i.e., the distortion below a 0.1% level.

Distortion rises with increasing output rates of change, until the class B current boost mechanism is actuated; then it levels off, even dropping somewhat. As frequency is increased further it remains substantially the same (but not constant). These behavior characteristics can be noted in the data of both the 531 and the 535, as well as the 1741S. At audio frequencies, the 535 and 1741S are nearly identical.

As a demonstration that distortion performance cannot be accurately predicted with a slew-enhanced device: the 531 has a 30V/µS slew rate specification while the 535 and 1741S specs. are 15V/µS and 12V/µS. Yet in terms of measured performance the 535 and 1741S are both appreciably better. The reason? Their basic (unenhanced) slew rate is faster than the 531 (at least for the samples tested here) and this parameter determines distortion performance below the class B trigger level.

FIG. I-18

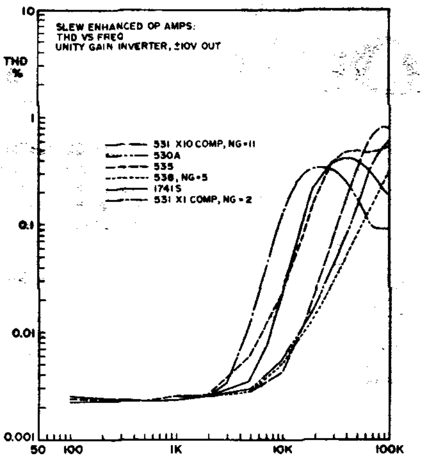


Fig.I-18 also plots the 538, a decompensated version of the 535, suitable for working gains of five or more. Since slew rate can be improved by the factor of compensation reduction, the 538 also features a x5 greater basic slew rate. As a result it will exhibit a low distortion characteristic to higher frequencies than will a 535, evident in the 535's curve.

The increase in frequency for a given distortion level is not exactly five times (as might be initially assumed), because the device must be used in a x5 gain condition which results, of course, in less feedback, and subsequently a somewhat higher measured distortion. Nevertheless the 538 is a substantial improvement over the 535, and is therefore a more attractive device.

An interesting proof of the validity of the higher (unenhanced) slew rate's value is shown in the performance of the 531 for a x10 compensation. This curve (Fig.I-18) is moved outward in frequency due to the smaller compensation capacitance and thus higher basic slew rate. This re-emphasizes the points made above in the discussion of variable compensation devices.

The 530A is one of the better performing devices shown in Fig.I-18, a more recent design which features improved input stage linearity and greater speed. Its performance is on a par with the x10 compensated 531 or the decompensated 538, but the 530A is a unity gain stable device.

As a group, slew enhanced devices can be effective in reducing slewing induced distortion, but on an absolute basis not as much as devices which increase slew rate by more direct means. The class B mechanism, in itself a non-linear effect, can (potentially at least) be a source of additional distortion. The most attractive devices in this group are the decompensated 538 which is reasonably clean at gains of five, the 531 (an externally compensated unit) which can be custom compensated for high stage gains, and the 530A, a faster, more linear unity gain stable device. Any of these units will be much cleaner if applied following the basic ground rules which minimize the approach of slew limiting.

The IM testing data which follow will give further insight into this conclusion, which is also supported by the outcome of the IM tests. However, while performance of unity gain slew enhanced devices can be exceeded by many other devices which are basically faster, keep in mind that even a slew enhanced device such as a x1 compensated 531 or a 535 is better than a 741 (or other <1V/µS slew rate device), since they avoid gross slew limiting.

Decreasing the transconductance of the input stage is a highly effective means of increasing a device's basic slew rate. A number of circuit techniques will accomplish this goal, but two of them yield outstanding measurable results in audio application.

The most direct method substitutes lower transconductance input stage devices, for example P channel JFET's or PMOS units, operating differentially and drain loaded. A bit later we'll discuss the performance of three designs which use this approach.

Another technique, which can be employed in virtually any op amp, uses emitter degeneration resistors. Designers have employed it in a large number of devices, the 318 and 518 being the most outstanding (fastest) examples. Emitter degeneration in a bipolar amplifier has drawbacks, however. The increased emitter current requires buffering to maintain a low DC input current, thus Darlington pairs are often used when it is applied. For audio, this has the serious drawback of adding additional undesirable noise sources. And emitter degeneration resistors themselves also add noise, so an emitter degenerated amplifier is by nature noisier than one which is not. In audio this type of device is therefore used only in higher level circuitry (preferably).

In op amp design history, one early use of emitter degeneration was "first generation" FET input IC op amps as typified by the 740, 8007, AD540, and NE536. This class of device typically uses a P channel JFET pair operated as source followers, which in turn drive an emitter degenerated bipolar PNP differential pair. Slewing rates achieved by this design are approximately 6V/µS, which is an order of magnitude better than "741" type performance.

Although the bandwidth of these amplifiers is the same as that of a 741, or 1MHz typical, the slewing rate improvement alone is sufficient to allow dramatic improvement in distortion performance. This is a point which should be underscored: an improvement in slew rate in a case of slew limiting can effect an improvement far beyond that of an equivalent bandwidth improvement, were slew rate to be held constant.

This is clearly evident in the THD vs. frequency performance of this class of devices, when compared with 741 or other similar slew rate units. Fig.I-19 plots the 8007, the AD540 (not to be confused with the NE540, discussed above), and the NE536. The specified typical slew rate for all these units is 6V/µS, but production variations yield samples above and below this mean. The performance of these samples could again almost be ranked by slew rate, at least at high frequencies.

Both the 8007 and the AD540 exhibit the classic slew limited THD curve, but the NE536, due to its higher slew rate, is stopped short of tracing out the classic pattern at 100kHz (due to equipment limits).

In the case of the NE536, the HF distortion is sufficiently low in this instance to warrant comparison with the equipment residual; and in fact near the 100kHz it is only slightly above the residual THD curve. At lower frequencies we see an anomaly, however, as both the 8007 and the AD540 have lower THD in the 2K to 20K range than the NE536. The differences are subtle, but measurable, and at this writing cannot be accounted for.

In perspective, any of these three amplifiers offers excellent performance, with THD below 0.01% to frequencies even above 20kHz. An amplifier which can achieve this kind of performance is in general quite good, and can be recommended without serious reservations, at least insofar as slew induced distortion is concerned. Again, this conclusion will be further supported by the IM test results to follow.

More recently, designers have introduced FET input amplifiers which use low transconductance FET input *differential pairs* to achieve higher slew rates. These may be termed "second generation" FET input op amps, as their design objectives seek to conquer the drawbacks of first generation designs. However, their overall audio performance is something of a mixed blessing. The three basic design approaches are the 356-357 series, which uses a P channel JFET input stage; the 3140, which uses a PMOS input stage; and the TL084, which uses a P channel JFET input/remainder bipolar type design.

The 356 has a 5MHz bandwidth and a 15V/µS slew rate, while the 357, a decompensated (minimum gain x5) version, has a 25MHz bandwidth and a 75V/µS slew rate. The 3140 has 4.5MHz bandwidth and a 9V/µS slew rate spec. The TL084 (a quad unit) has a 3MHz bandwidth and a 7V/µS slew rate. Although all these amplifiers appear to be eminently suitable for audio, in practice they are not and we must add qualifiers in at least two cases.

The 356/357 design has an inherent slew rate asymmetry built into it, slewing faster on negative slopes than positive. This gives rise to higher than "ideal case" distortion (for an equivalent slew rate, symmetrical amplifier). Easily measurable, at least in the case of the 356, this flaw causes an otherwise reasonably good amplifier to achieve less than its full potential. The 357, because it slews much faster, moves this "higher than ideal" distortion upward in frequency. While this minimizes the asymmetry defect, the 357 is also limited to gains of five or more, which makes it not quite as effective as the 356 for general purpose use.

The 3140 also shows asymmetrical slew, faster (+) than (-). The (-) slew rate is limited by a speed problem in the output stage which will produce a sudden 1% or more rise in THD at 30-40kHz, while very low below these frequencies. This problem is *not inherent* in the 3140's voltage amplification stages, however, and the output stage can be "fooled" by forcing a class A pulldown current to the V- rail, which removes the restriction and makes the slew rate nominally symmetrical. Operated in this way the data indicate it is one of the higher performance devices tested for SID.

In Fig.I-20 the reader can compare these factors on a common basis. The symmetrically slewing 3140 outperforms the 356, although the 356 has a higher slew rate. The 3140 is actually fairly close to the equipment residual over this range.

The TL084 is free of the problems of slew asymmetry; in fact, on the sample plotted none was measurable. The TL084 produced further evidence of the validity of the slew symmetry criterion, yielding higher performance than the faster 356. It even slightly betters the 3140 in the 10-30kHz region. It did appear to have a higher residual noise level at lower frequencies, however, which may limit its use for low level stages. From other than the noise standpoint, the TL084 appears to be the best of the currently available general purpose quad amplifier types, as it conquers the major limitation of slew rate and has a higher than average bandwidth.

We can make some further comparison with the first generation FET amplifiers, for instance the 3140 and the NE536, which slewed at about the same speed. The 3140 shows lower distortion, which would follow, as it has wider bandwidth and thus more corrective feedback. This would follow logically, since given two amplifiers with similar (symmetrical) slew rates, the wider bandwidth device will perform better, if we are comparing two devices whose condition is not limited. If we compare the TL084 with the NE536, we see the TL084 has less distortion in the 20-30kHz region since it has higher feedback than the NE536. Further up the frequency scale, where the TL084 begins to slew limit, the NE536 has the edge due to its faster slew rate.

The "dielectrically isolated" class of amplifiers perform quite well both in slew rate and bandwidth. Dielectric isolation allows very high op amp speeds, generally an order of magnitude higher in both bandwidth and slew rate. Impressive performance results when designers combine this technique with a good symmetrical slew rate.

Fig.I-21 illustrates THD performance of two dielectrically isolated op amp devices, the 2620 and 2525. Both are externally compensated, high slew rate, wide bandwidth devices. The 2620, however, can be opened up to a higher bandwidth, and will have slightly greater feedback for a given gain setting than the 2525, as the performance data reveal.

Compensated for unity gain, the 2620 sample slewed at 5.7V/µS but, as the data show, has excellent THD performance in the audio region, even though slew limited at just below 100kHz. This underscores the value of the extra bandwidth (8MHz here), as the 1MHz AD540 slewing at 5.7V/µS does not do as well (see Fig.I-19).

With no compensation, the 2620 is stable at gains of five or more and, as the noise gain of five plot shows, THD which is still low, without apparent slew limiting. Indeed, this curve is only slightly above the residual of the Sound Technology 1700B, whose oscillator uses a x1 compensated 2620 type device. The distortion rise towards 100kHz is the approach of slew limiting.

The 2525 performance shows that slew rate alone will not do the job completely; high feedback is also needed to achieve the lowest distortion. This device slews much faster than the 2620 (over 60V/µS measured) but has somewhat less feedback for the same gain setting. It also appears to have slightly higher open loop distortion, which may be a limiting factor.

Perhaps now the reader can begin to appreciate that we are speaking of differences in superlatives--either device for any condition shown is quite good, and will yield excellent low distortion performance.

A most interesting general class of op

FIG. I-19

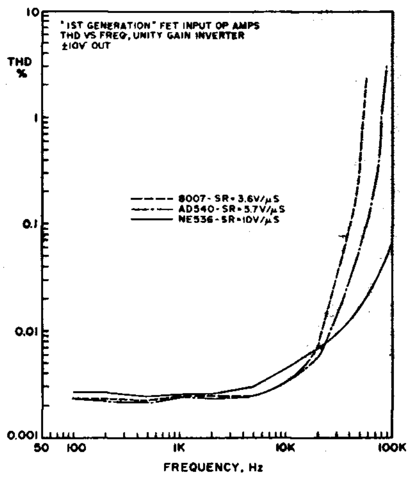


FIG. I-20

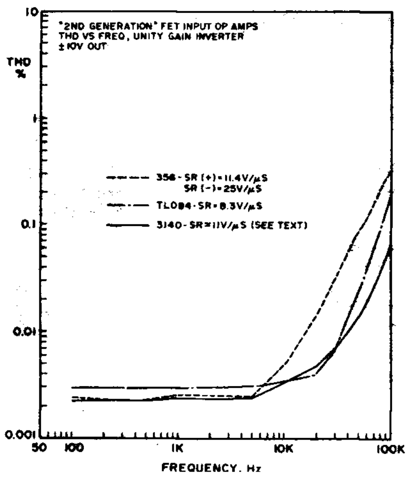


FIG. I-21