A FULLY IN-BAND MULTITONE TEST FOR

TRANSIENT INTERMODULATION DISTORTION

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ABSTRACT

A specially designed three tone intermodulation test for transient intermodulation distortion (TIM) is proposed. The test employs three tones to simultaneously produce even-order difference and odd-order triple beat distortion products near 1 kHz, and results in extremely simple, yet sensitive instrumentation. A significant advantage of the test is that the stimulus and response both lie in-band.

INTRODUCTION

The heightened awareness of transient intermodulation distortion (TIM)[1,2,3] brings with it the need for efficient and economical testing techniques which can objectively measure this distortion while providing good correlation with subjective listening test results. Three tests are currently in use: the sine-square DIM,[4] 20-kHz THD,[2] and the polarity-modulated sawtooth.[5] Each of these tests has various individual disadvantages (e.g., expensive instrumentation, unrealistic test signal characteristics, insensitivity to "soft" TIM, etc.), but they all suffer from the fact that either much of the stimulus (test signal) or much of the response (distortion products) spectra lie considerably out-of-band. This can cause testing problems or unrealistic results in many band-limited or nonflat systems. Particularly good examples are tape recorders and phono preamplifiers. Another example of growing importance is digital audio systems, where anti-aliasing filters are employed which introduce a very sharp cutoff just above 20 kHz.

The test proposal here is a modification of the CCIF two-tone difference frequency IM test. The CCIF test is adequately sensitive and does not require expensive instrumentation, but has the fatal disadvantage of almost total insensitivity to odd-order distortion mechanisms. To retain the advantages and eliminate the odd-order insensitivity problem, a third tone is added. The frequencies are selected to simultaneously produce a triple-beat product (A-B-C) slightly below 1 kHz and a difference-frequency product (B-C) slightly above 1 kHz. We will refer to the new test as the "multitone intermodulation test" (MIM).

Because the peak signal slope of the test is not grossly in excess of that of worst-case program signals, and because the measured product falls in the most sensitive portion of the audible spectrum, good subjective correlation can be expected.

THE NATURE OF TIM

In discussing audio amplifier distortion issues, it is convenient to divide distortion types into two categories: static and dynamic.[4] Static distortion levels depend only on the amplitude of the signal, while dynamic distortion levels depend on both the amplitude and frequency of the signal. Alternatively, one may say that dynamic distortion is a function of the rate-of-change of the signal.[2] In general, low-frequency distortion tests, such as SMPTE IM and 1-kHz THD, measure static amplifier distortions, while high-frequency distortion tests, such as 20-kHz THD and CCIF (e.g., 19- and 20-kHz difference tone) measure dynamic amplifier distortions. Transient intermodulation distortion (TIM) is a type of dynamic intermodulation distortion produced by a particular mechanism.

In any case, distortion is inevitably produced by a nonlinearity somewhere in the amplifier, and a given nonlinearity will produce measurable distortion products (either harmonic or intermodulation) with any test which adequately exercises the nonlinearity. As an example, a simple high frequency sinusoid adequately exercises the TIM mechanism in an amplifier and produces an easily measurable THD product indicating the presence of TIM.[2]

The TIM mechanism is quite simple and is easily understood by referring to the highly simplified power amplifier schematic shown in Fig. 1. The differential pair consisting of Q1 and Q2 acts as a transconductance amplifier. Its current output drives the base circuit of predriver Q3, which in turn drives the output stage. At mid and high frequencies the predriver stage acts as an integrator due to the action of compensating capacitor C3; the signal current from Q1 is integrated to form the drive voltage for the output stage. As a result, the signal level in the first stage is proportional to frequency for a given output. In the time domain the signal in the first stage is the time derivative of the output signal, and so its amplitude is proportional to output rate-of-change. Distortion produced by amplifier stages such as these which are situated prior to the point of frequency compensation, and which is a function of the rate-of-change as a result, is called transient intermodulation distortion (TIM).

The differential pair is characterized by a well-behaved symmetrical static nonlinearity (the tanh function). Thus, TIM is a static distortion mechanism made dynamic in behavior by the fact that the nonlinearity is situated in a part of the circuit where signal amplitudes are proportional to frequency (or output rate-of-change in the time domain sense). If the differential stage is driven to clipping by the signal amplitudes it must handle, then the well-known phenomenon of slew rate limiting occurs, and so-called "hard" TIM results. If the signal amplitudes in this stage are enough to cause distortion but not clipping, then so-called "soft" or subslewing TIM is produced. The mechanism is simple, well behaved, and well understood. There is no mystery about it.

Because TIM depends on the rate-of-change of the program signal, a realistic appraisal of TIM mechanisms and measuring techniques requires some consideration of expected program characteristics. Based on discussions elsewhere, it can be concluded that program sources are not as fast as some might think, a normalized rate-of-change (peak slope to peak amplitude ratio) of 0.05 to 0.075 (V/μs)/V seeming to be the upper limit.[6,7,8] This corresponds to a power bandwidth of little more than 10 kHz or so, and less than a 3 V/μs rate-of-change for a 100-watt amplifier. This suggests that outright slew rate limiting, even on amplifiers with fairly high levels of TIM, is an extremely rare event. The real problem is clearly subslewing TIM.

It is also worth pointing out that what we hear as TIM is undoubtedly intermodulation products which show up in the midband as the result of complex intermodulation interactions among several high-frequency components. This observation is important when evaluating the effect of feedback factor on TIM, because feedback factor is a function of frequency and reduction of distortion products by feedback depends on the feedback factor at the product frequency.

It is tempting at this point to draw some conclusions about the use of low-pass filters ahead of power amplifiers in the quest for TIM-free reproduction. Although such a filter can prevent slew rate limiting when the input signal is, say, a square wave with a 10-ns risetime, and may improve amplifier performance with certain TIM tests, it will do little, if anything, toward prevention of subslewing TIM under normal program conditions because it will not significantly affect the rate-of-change of a signal characterized by a maximum power bandwidth of only about 10 kHz. The LPF seems only useful for eliminating high-level ultrasonic disturbances which should not exist in the first place. We can conclude from this that so-called "non-slew limited" amplifier designs (which often incorporate an input LPF to guarantee that slewing cannot occur, regardless of the input signal risetime) do not necessarily achieve subjectively better TIM performance than ordinary designs.

EXISTING TESTS FOR TIM

Three tests now exist for measuring the TIM performance of an amplifier. They are the sine-square DIM test proposed by Otala,[4] high-frequency THD,[2] and the polarity-modulated sawtooth recently proposed by Sansui.[5] It should be pointed out that none of these tests makes any distinction between TIM and any other form of dynamic intermodulation distortion; it is not likely that the ear does so, either. An important characteristic of all dynamic intermodulation tests is peak rate-of-change of the test signal, since this is the real function driving the nonlinearity, rather than amplitude alone. As we will see shortly, some of the tests resort to rather high rates-of-change to achieve acceptable sensitivity.

The measurement floor of a test is just as important in assessing the merit of a test as the sensitivity. A test which produces large numbers but which also has a high measurement floor is not really more sensitive or meritorious than a test which produces smaller numbers and has a correspondingly lower measurement floor. In a sense, what we are really concerned about is the dynamic range of the test.

It must be recognized that the various distortion tests produce a number which is merely a metric for actual performance, and whose absolute value is of limited significance when compared to a number generated by a different distortion test. If an individual claims to be able to hear 0.01 percent THD, he is merely saying that he can hear the effect of the distortion products produced under program conditions by an amplifier which measured 0.01 percent THD in the laboratory.

DIM-30

The sine-square test was proposed specifically for testing TIM in audio amplifiers.[4,10] The test combines a 3.18-kHz square wave and a 15-kHz sine wave in a 4:1 peak amplitude ratio, and the square wave is filtered by a single pole at 30 kHz. The test is referred to as DIM-30, denoting dynamic intermodulation distortion with 30-kHz filtering. A more stringent test with 100-kHz filtering has also been proposed.[4] The various intermodulation products of 15 kHz with 3.18 kHz and its integer multiples are measured on a spectrum analyzer, summed in an RMS fashion and referred to the 15-kHz amplitude to arrive at a distortion percentage.

The fairly high normalized rate-of-change of 0.32 (V/μs)/V of the DIM-30 test readily excites dynamic distortion mechanisms. However, the sensitivity of the test is not quite as great as one might expect because the rate-of-change duty cycle is fairly low: the slope exceeds half its peak value for only about 6 percent of the time. A more significant limitation of this test is the fairly high distortion floor: a good spectrum analyzer with 90 dB of dynamic range will yield a floor of 0.035 percent.[8] This impairs the ability of the test to measure subslewing TIM.

Because the test signal rate-of-change depends heavily on out-of-band (>20 kHz) harmonics of the square wave, this test can be led to give somewhat optimistic results for amplifiers incorporating front-end low-pass filters. In general, however, the test yields useful information and a very interesting spectral display of amplifier performance.

The primary disadvantage of this useful test is the expensive instrumentation and extremely tedious procedure.

20-kHz THD

Although seemingly not very dynamic in appearance, a sine wave of sufficiently high frequency is more than adequately dynamic in terms of exercising amplifier TIM mechanisms, and so high-frequency THD measurements have been suggested as a good test for TIM.[2] For single-number tests 20-kHz THD (THD-20) is preferred because it developes the largest peak slope/peak amplitude ratio (0.125 (V/μs)/V) for any in-band sinusoid.

At a given peak-to-peak amplitude, THD-20 is not quite as sensitive as DIM-30 because of the smaller peak slope; however, its measurement floor is at least an order of magnitude lower than that for DIM-30. It is a more sensitive test for soft TIM and has a greater overall dynamic range.[9] THD analyzers with adequate sensitivity are moderately expensive, but in widespread use. Of particular significance is the fact that most amplifier specifications include a quote of THD up to 20 kHz at rated power.

While the THD-20 test is not misled by amplifiers with front-end low-pass filters, it is misled if the overall bandwidth of the DUT is not at least 100 kHz. This can be a serious problem in testing phonograph preamplifiers, for example.

POLARITY-MODULATED SAWTOOTH

The polarity-modulated sawtooth measurement technique was recently proposed by Sansui, its primary advantage being inexpensive instrumentation.[5] In practice, an unfiltered 20-kHz sawtooth waveform has its polarity reversed at approximately a 78-Hz rate. Thus, its asymmetry reverses at this rate. Without reversal, application of the high-frequency, asymmetrical sawtooth signal to an amplifier will cause the amplifier's even- or odd-order nonlinearities to generate a dc offset whose magnitude depends on the severity of the nonlinearity. The dc offset due to even-order nonlinearities is primarily formed by ordinary second harmonic distortion of the sawtooth fundamental. The dc offset due to odd-order nonlinearities is primarily due to "2A-B" type intermodulation between the sawtooth's fundamental and second harmonic. In the event that these offsets are of opposite polarity, one might speculate that an optimistic reading could result. The periodic polarity reversal merely "chops" this dc offset into an easily measured low-frequency ac signal. The much higher frequency test signal is eliminated in the analyzer by relatively inexpensive low-pass filtering.

This test derives most of its sensitivity from the extremely sharp unfiltered sawtooth edges which it applies to the amplifier under test. The normalized rate-of-change is extremely high (probably at least 10 (V/μs)/V) and consequently the test signal rate-of-change is very large. Amplifiers without input LPFs with moderate, but adequate, slew rate, and which test extremely well in the previous tests, can be expected to slew rate limit on this test and give an unjustifiably poor showing. The subjective correlation of this test is also questionable because its risetime is so much faster than that of music.

Finally, because this test depends so heavily on extreme signal slope (and on out-of-band sawtooth harmonics) it will be easily misled in its assessment of TIM (particularly subslewing TIM) by amplifiers which incorporate input low-pass filters. The low-pass filter not only reduces the peak signal slope, but also reduces the waveform asymmetry and second harmonic level, resulting in a particularly serious loss in sensitivity to odd-order nonlinearities.

A MULTITONE TIM TEST

Although each of the existing tests has merit, each also has some disadvantages. It seems that the following list of desirable test characteristics would suffice to describe an almost ideal TIM test: (1) inexpensive instrumentation, (2) simple measurement procedure, (3) good sensitivity (particularly to midband even- and odd-order IM products), (4) in-band stimulus and response, (5) good subjective correlation due to music-like test signal risetimes. None of the existing tests meet all of these goals. The multitone IM test to be presented here represents an attempt to get closer to this ideal.

The multitone intermodulation test (MIM) is a variation of the well-known CCIF two-tone IM test in which two high-frequency tones spaced apart by a small frequency difference (e.g., 19 and 20 kHz) are applied to the unit under test and the difference frequency IM product is measured. The tone sources need not be very low in distortion, and simple low-pass filtering permits separation of the distortion product from the stimulus, thus permitting excellent sensitivity. The CCIF test has been used with some success for measurement of high-frequency distortion, but it is sensitive only to even-order distortion mechanisms. Its total insensitivity to odd-order distortion mechanisms, which are the more prominent sources of distortion in many contemporary designs, render it useless as a reliable general purpose TIM measurement tool. If a spectrum analyzer or other sharp cutoff filtering technique is used to look at the "2A-B" products as well, which in this example lie at 18 and 21 kHz, then the test will also be sensitive to odd-order products; under these conditions, however, the instrumentation cost becomes high.[11]

In order to retain the advantages of the CCIF test while incorporating odd-order sensitivity, a third tone has been added. The three frequencies are chosen so that the three tones produce a triple beat product (A-B-C) at slightly below 1 kHz, while two of the tones produce a CCIF-like difference frequency product (B-C) at slightly above 1 kHz. Specifically, the three equal-level tones are at 9.00, 10.05 and 20.00 kHz, resulting in odd-order products at 950 Hz and even-order products at 1050 Hz. It should be emphasized that the difference frequency product contains contributions from all even-order mechanisms, not just second order. Similarly, the triple beat product contains contributions from all odd-order mechanisms, not just third order.[12]

The even- and odd-order products are selected to lie fairly close to each other in frequency so that both products can be passed through a relatively narrow bandpass filter centered about 1 kHz, improving immunity to noise generated in the unit under test.

The photos in Figures 2-6 illustrate the appearance of the test in the frequency and time domains. Figure 2 shows the appearance of the undistorted test signal on a spectrum analyzer (2 kHz/div, 30-Hz BW), while Fig. 3 illustrates the distortion products added to the spectrum when the test signal is passed through a 741 operational amplifier operating at an inverting gain of 10 at an output level of 4.2 V p-p. The products of interest here are seen at the extreme left of the photo at about 1 kHz. Notice there are two unequal very closely-spaced products there; these are the odd- and even-order products. Fig. 4 is a "closeup" centered on 1 kHz (200 Hz/div, 10-Hz BW) clearly showing the odd-order product on the left and the smaller even-order product on the right.

The top oscilloscope trace in Fig. 5 illustrates the appearance of the three-tone MIM test signal when the sweep is synchronized to the filtered and extracted distortion products shown in the lower trace. Finally, the distortion products at 950 and 1050 Hz are shown with a slower sweep in Fig. 6. The "amplitude-modulated" appearance is due to the two products beating against each other. If the products were equal in amplitude, the apparent modulation depth would be 100 percent.

The distortion percentage will be defined here as the value of the 950-Hz and 1050-Hz distortion products, measured together on an average responding ac voltmeter, referred to the rms value of a sine wave of the same peak-to-peak amplitude as the three-tone MIM test signal. In the case of power amplifiers, the test power level will be defined as the average power corresponding to a sine wave of the same peak-to-peak amplitude as the MIM test signal.

The choice of 1 kHz as the approximate frequency where products are made to appear is somewhat arbitrary, but is based on two considerations. First, choosing a higher frequency band requires sharper filtering for a given level of test signal rejection. The second consideration is based on the earlier observation that what is normally heard as a result of high-frequency distortion is intermodulation products folded down into the midband rather than high-frequency harmonics. Because the ear is most sensitive near 1 kHz, the intermodulation products of this test have been chosen to appear there. With this choice, the test accurately takes into account any IM distortion product reduction at midband frequencies afforded by negative feedback which may be larger in the midband than at the upper band edge. THD-20, for example, does not take this possibility into account (THD-20 may actually be somewhat pessimistic in this regard because its second- and third-harmonic amplitudes depend on the feedback factors at 40 kHz and 60 kHz, respectively).

Some may wonder if this test, not being "impulsive" in nature, will adequately exercise and expose TIM distortion mechanisms. The answer is a clear "yes," for the same reasons that 20kHz THD measurements do: exercise of the TIM mechanisms depends primarily on the peak slew rate of the test signal, and very little on the waveshape of the test signal. The peak slew rate of the three-tone test signal is approximately two-thirds that of a full-amplitude 20-kHz sinusoid (i.e., about 0.084 (V/μs)/V), still significantly more than worst-case program (0.05 (V/μs)/V).[6,7,8] Because of the smaller peak slew rate stimulus compared with other TIM tests, somewhat smaller distortion percentages are produced from a given nonlinearity operating at a given peak-to-peak voltage level. However, the greatly reduced measurement floor makes up for this in terms of overall measurement technique dynamic range.

Also, because of its somewhat lower peak test signal slew rate, MIM is somewhat less sensitive than THD-20 or DIM-30 to certain forms of "hard" TIM mechanisms, in which an amplifier with a relatively small slew rate is exceptionally linear right up to its slew rate limit and then suddenly generates TIM when pushed beyond that limit. Such an amplifier whose slew rate was between 8.4 and 12.5 V/μs and whose rated output was 100 V p-p would be a case in point. Presumably the three-tone test would show no TIM, while THD-20 or DIM-30 would indicate TIM at rated output. However, with program the amplifier would not enter the TIM-producing slewing region and the three-tone test would therefore be accurate in characterizing the amplifier as TIM-free. Such a case is very unusual, and would be more than adequately handled if the three-tone test results are quoted in combination with rated slew rate. Rated slew rate will always handle the outright slewing (i.e., "hard" TIM) condition; it is the "soft" TIM which is what is usually heard and for which better measuring techniques are needed.

INSTRUMENTATION

As mentioned earlier, simplicity and economy of instrumentation are important virtues of the MIM distortion measuring technique, and this is illustrated by the simplified block diagrams of the MIM test signal generator and MIM product analyzer shown in Figures 7 and 8 respectively. With the exception of the ac VTVM, the entire generator/analyzer prototype fits in a 3-1/2 by 6 by 10 inch box.

The generator consists of three simple fixed-frequency Wein bridge oscillators whose outputs combine at an inverting summer amplifier to form the composite test signal. The virtual ground of the summer operational amplifier minimizes intermodulation among the oscillators due to the summing operation. Metal shields isolate the oscillators from each other and from the summing amplifier to prevent intermodulation due to coupling of other signals into the oscillators.

A major advantage of the MIM technique is the ability to utilize inexpensive signal sources for each of the three component frequencies without serious concern for their harmonic distortion characteristics. The oscillators used here are extremely simple in design, utilizing a single operational amplifier and a FET. They produce 5 volts, rms at about 0.01-percent THD; larger values of THD would still be acceptable. The oscillators were, however, carefully designed to produce very low noise, as the sum of source, UUT, and analyzer noises is the major contributor to the measurement floor of the system. Distortion produced by the summer is well below the system measurement floor.

Because there is over three octaves of frequency difference between the product frequency and the lowest test signal frequency, very sharp and precise filtering is unnecessary in the MIM product analyzer. As shown in Fig. 8, the test signal from the UUT is first processed by a pair of 2-kHz third-order Butterworth low-pass filters to attenuate the original test signal components by over 70 dB while introducing no significant loss in the vicinity of 1 kHz. The filters are of the simple unity-gain voltage follower design utilizing a single operational amplifier.[13] Each filter is followed by 20 dB of gain to maintain a good signal-to-noise ratio.

To minimize the product detection noise bandwidth and to achieve further attenuation at the test signal frequencies, the test signal from the UUT is next passed through a fourth-order Butterworth bandpass filter whose bandwidth is about 150 Hz and whose gain is approximately 10. A standard ac VTVM completes the MIM product analyzer. The gain of the analyzer is set to be 1000 at 1 kHz, so with a 1.414-V peak test signal level at the input, the analyzer sensitivity is 0.0001 percent per millivolt as read from the ac VTVM.

The measurement floor of the generator/analyzer combination is 0.0002 percent with a 1.414-V peak signal level into the analyzer, and is due almost entirely to thermal noise. A redesign of the first analyzer filter could push this figure below 0.0001 percent, but in most practical situations the thermal noise of the UUT will set the measurement floor. For example, a 100-watt amplifier with a 100 dB S/N ratio (20 kHz flat) will generate about 28 μV of noise at its output in the noise bandwidth of the analyzer. At the maximum 80-V p-p test level this will result in an additional noise of 1.0 μV at the analyzer input. This is less than the analyzer's 2 μv of referred input noise and will therefore only increase the measurement floor to about 0.00022 percent. However, at a much smaller 2.8-V p-p test level, the full 28 μV of amplifier noise will appear at the analyzer input and result in a measurement floor of about 0.0028 percent.

For comparison, THD-20 also has a noise floor which may be dominated by UUT noise. In this case, however, the floor is higher by a factor of 20-30 because the measurement bandwidth must be on the order of 100-200 kHz unless a spectrum analyzer is used.

EXPERIMENTAL RESULTS

In order to see how the multitone IM test compares with others in practice, THD-20, DIM-30 and MIM were measured and plotted for five circuits. The results, representing performance for four operational amplifier configurations and one power amplifier, are shown in Figures 9-13.

A 741 operational amplifier operating in the inverting unity gain configuration was first measured, and the results are shown in Fig. 9. The inverting configuration was chosen to eliminate distortion due to high-frequency common-mode effects.[2] In this configuration the amplifier exhibited a 500-kHz bandwidth and a ±0.65-V/μs slew rate. The dashed lines through the distortion curves indicate the point at which the test signal's peak rate-of-change equals the device slew rate.

All three tests indicate a similar trend of distortion as the test level is increased, with a somewhat faster rate of rise as the slew rate limit is approached. Below the level at which the DIM-30 signal causes slewing, the tests track each other quite well with a more or less constant decibel difference: THD-20 lies 4-7 dB below DIM-30, while MIM lies 30-35 dB below DIM-30. Although MIM lies 30-35 dB below DIM-30, its measurement floor for the test is only 0.00022 percent (not shown), 38 dB below that for DIM.

Figure 10 illustrates the results for the same 741 operational amplifier operated at an inverting gain of 10. Here the closed-loop bandwidth is approximately 75 kHz, while the slew rate is still about ±0.65 V/μs.

With the exception that the distortion levels are somewhat higher due to the smaller feedback factor, the relative behavior of the three tests is about the same, with MIM typically 27 dB below DIM-30. In this case, the MIM measurement floor is only 23 dB below the DIM-30 floor. The increase in the MIM measurement floor here is due to the increased amplifier noise produced by the 741 in the X10 configuration.

Figure 11 shows the same data for a 748 operational amplifier externally compensated with 4 pF and operated at a gain of 10. This amplifier is similar to the 741 with the exception that it is externally compensated. Because the lighter compensation increases the slew rate to about ±2.9 V/μs, greatly reduced TIM is expected, and this is confirmed by the curves.

Figure 12 illustrates further reduction in TIM when the 748 operational amplifier is operated with a smaller 2 pF compensating capacitor which yields a ±4.8-Vμs slew rate. As expected, all three measures of TIM show reductions.

Test results for a power amplifier are shown in Fig. 13. This 70-watt amplifier, of approximately 1970 vintage, was designed without particular concern for issues of TIM and slew rate (4 V/μs). It also uses a fairly slow quasi-complimentary output stage, so TIM is not the only significant source of dynamic distortion. Again, MIM is typically 27 dB below DIM-30 for levels less than those which cause slewing on the DIM-30 signal. At higher levels, a slightly greater separation is evident. The behavior of the THD-20 curve, with its rather shallow slope, seems rather anomalous.

CONCLUSION

A new method for measuring transient intermodulation distortion and other forms of dynamic amplifier distortion has been proposed. The primary advantages of the test are inexpensive instrumentation, simple measurement procedure, and fully in-band stimulus and response. The latter advantage allows the test to be utilized in many bandlimited systems where other dynamic distortion tests might not work properly.

Although the test is not as stringent as others in terms of peak rate-of-change, and as a result yields smaller distortion percentages, correlation with other dynamic distortion tests is good and dynamic range is similar. Because the test does not resort to unrealistically high rates-of-change to stress the amplifier under test, good subjective correlation can be expected.

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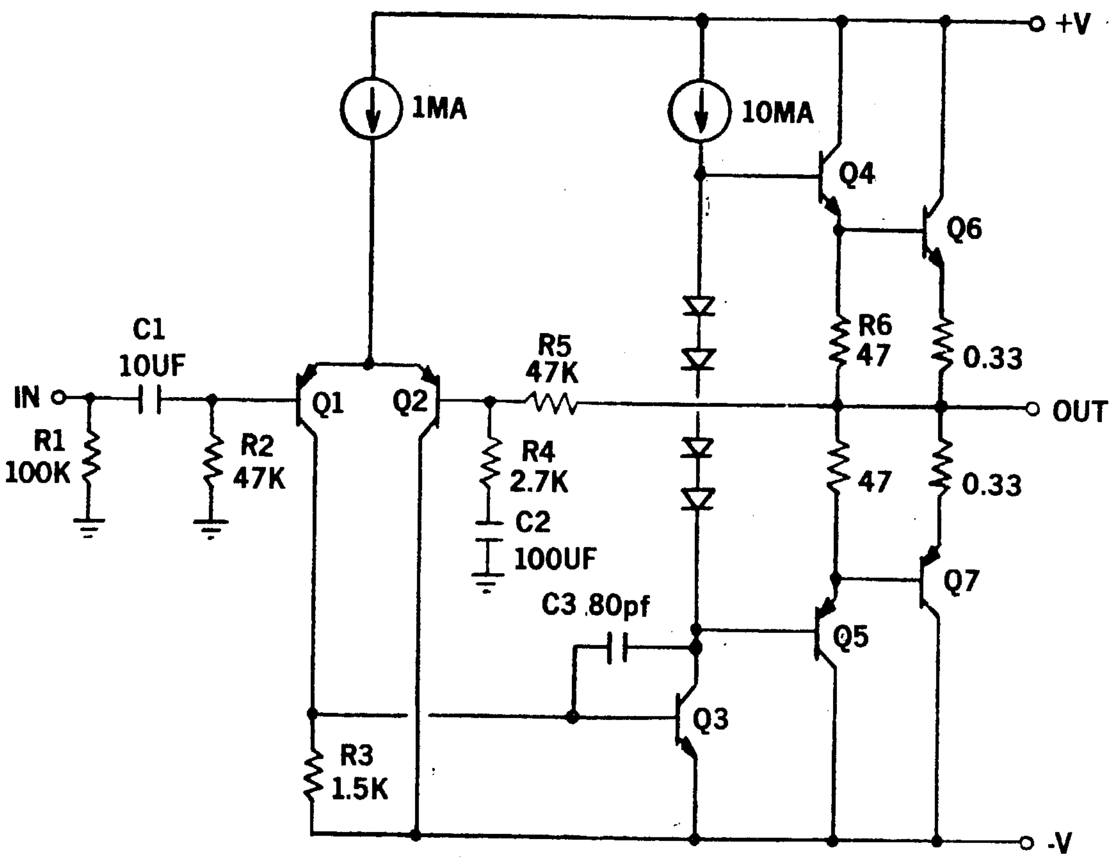


FIGURE 1: A Highly Simplified Power Amplifier

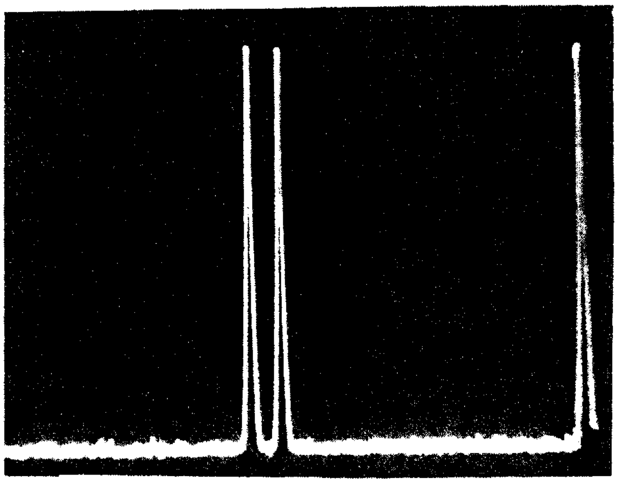


FIGURE 2: Spectrum of the MIM test signal (2kHz/div, 30Hz BW).

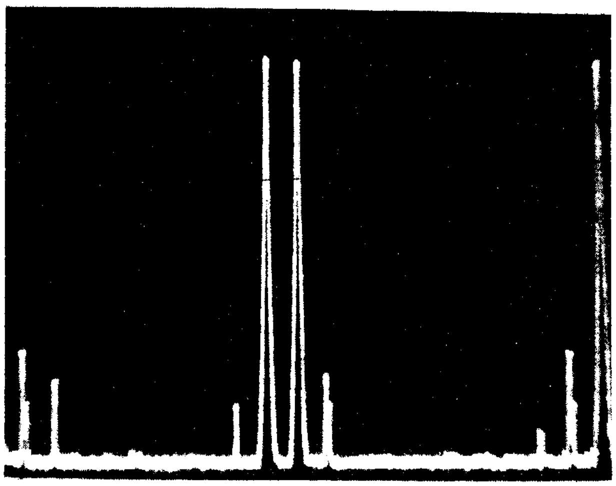


FIGURE 3: MIM spectrum including distortion products produced by a 741 op-amp operating at a gain of -10 at a level of 4.2Vp-p.

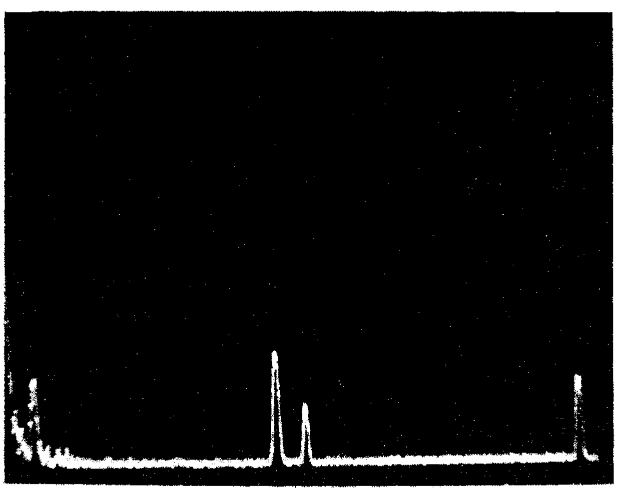


FIGURE 4: Closeup of the MIM products centered near 1kHz for

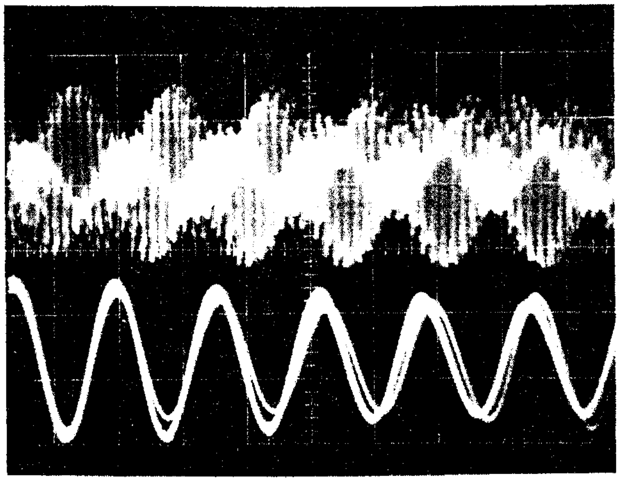


FIGURE 5: Appearance of the MIM test signal (top trace) and the extracted MIM distortion products (bottom trace). Sweep synchronized to bottom trace.

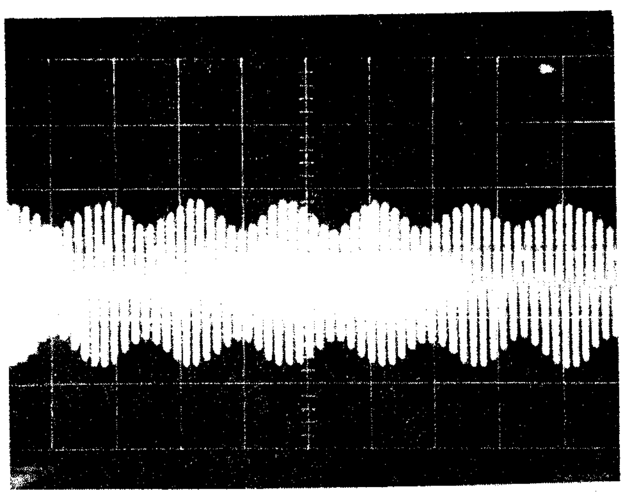


FIGURE 6: Extracted MIM distortion products as viewed with a slower sweep than in Fig. 5 and synchronized to envelope. Note "amplitude modulated" appearance due to presence of both even- and odd-order distortion products.

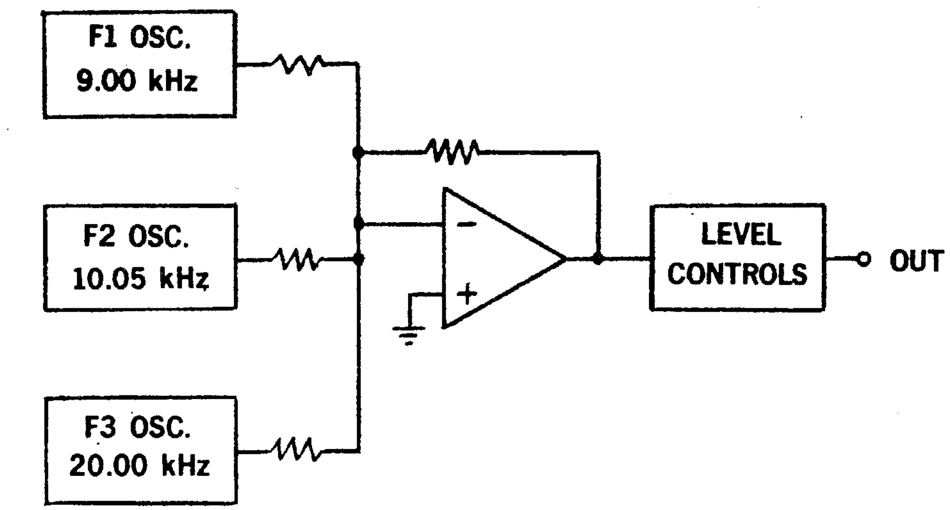


FIGURE 7: MIM Test Signal Source

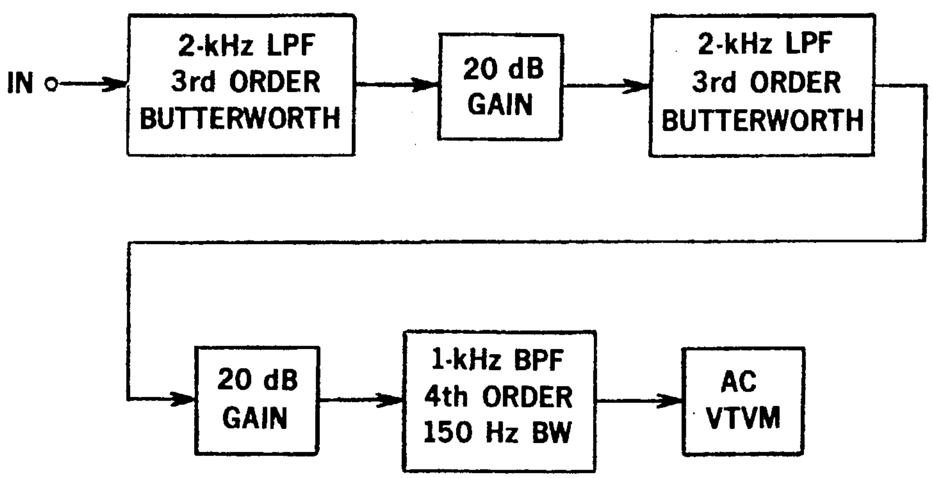


FIGURE 8: MIM Product Analyzer

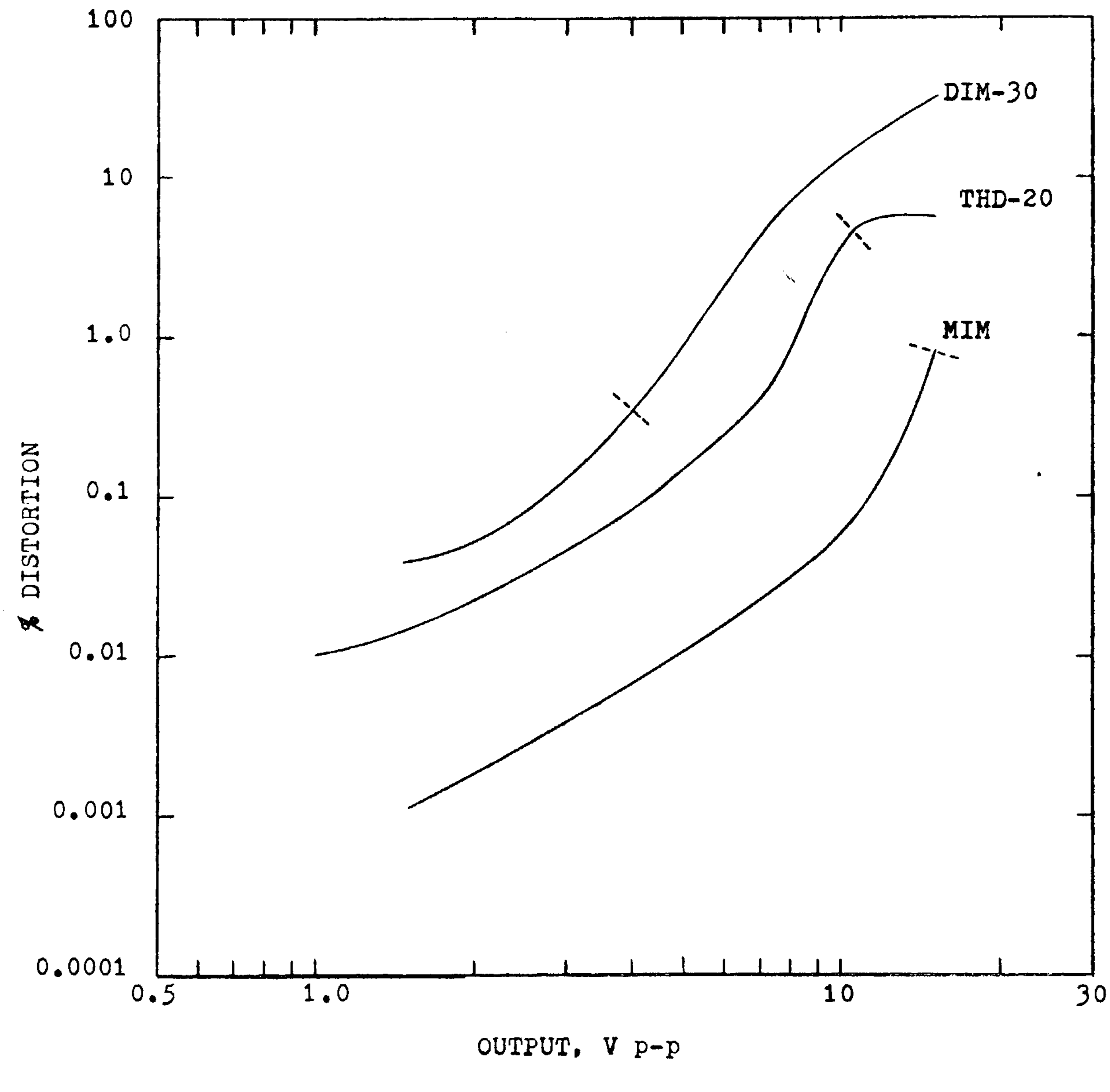


FIGURE 9: Distortion characteristics of a 741 operational amplifier operating as a unity-gain inverter ($V_S = \pm 12V$).

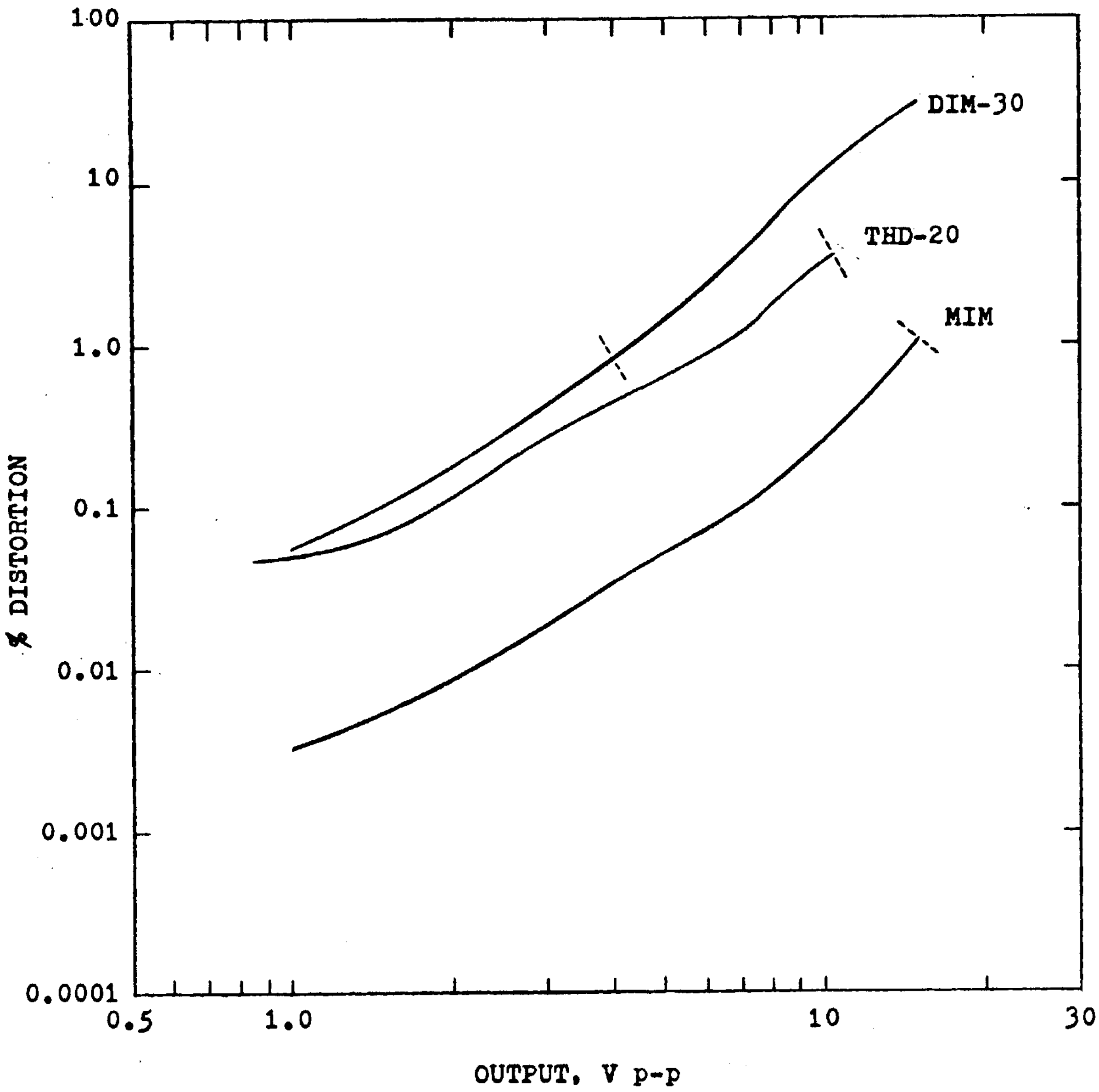
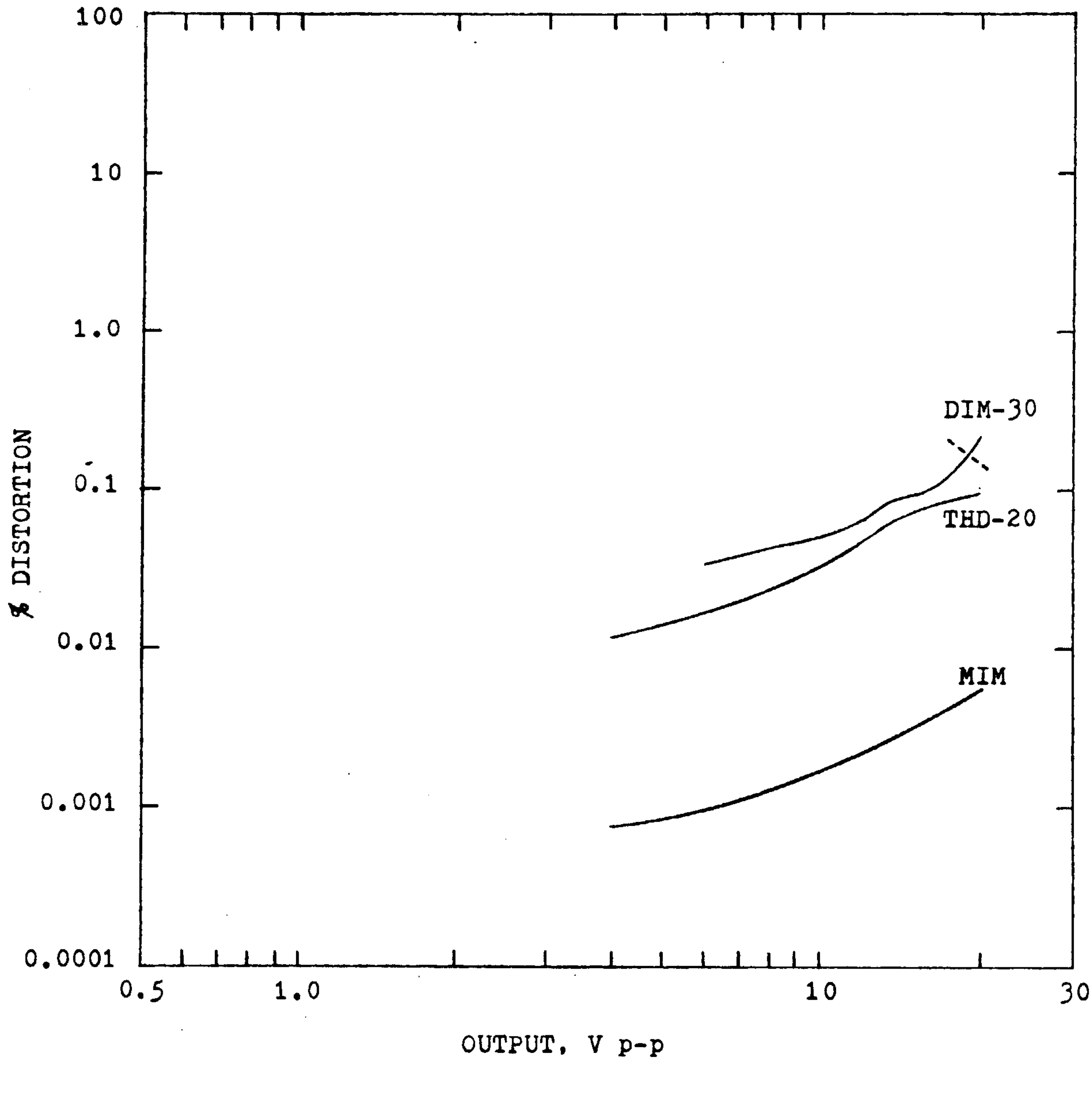


FIGURE 10: Distortion characteristics for a 741 operational amplifier operating at an inverting gain of 10.



FIUGRE 11: Distortion characteristics for a 748 operational amplifier externally compensated with 4 pF and operated at an inverting gain of 10.

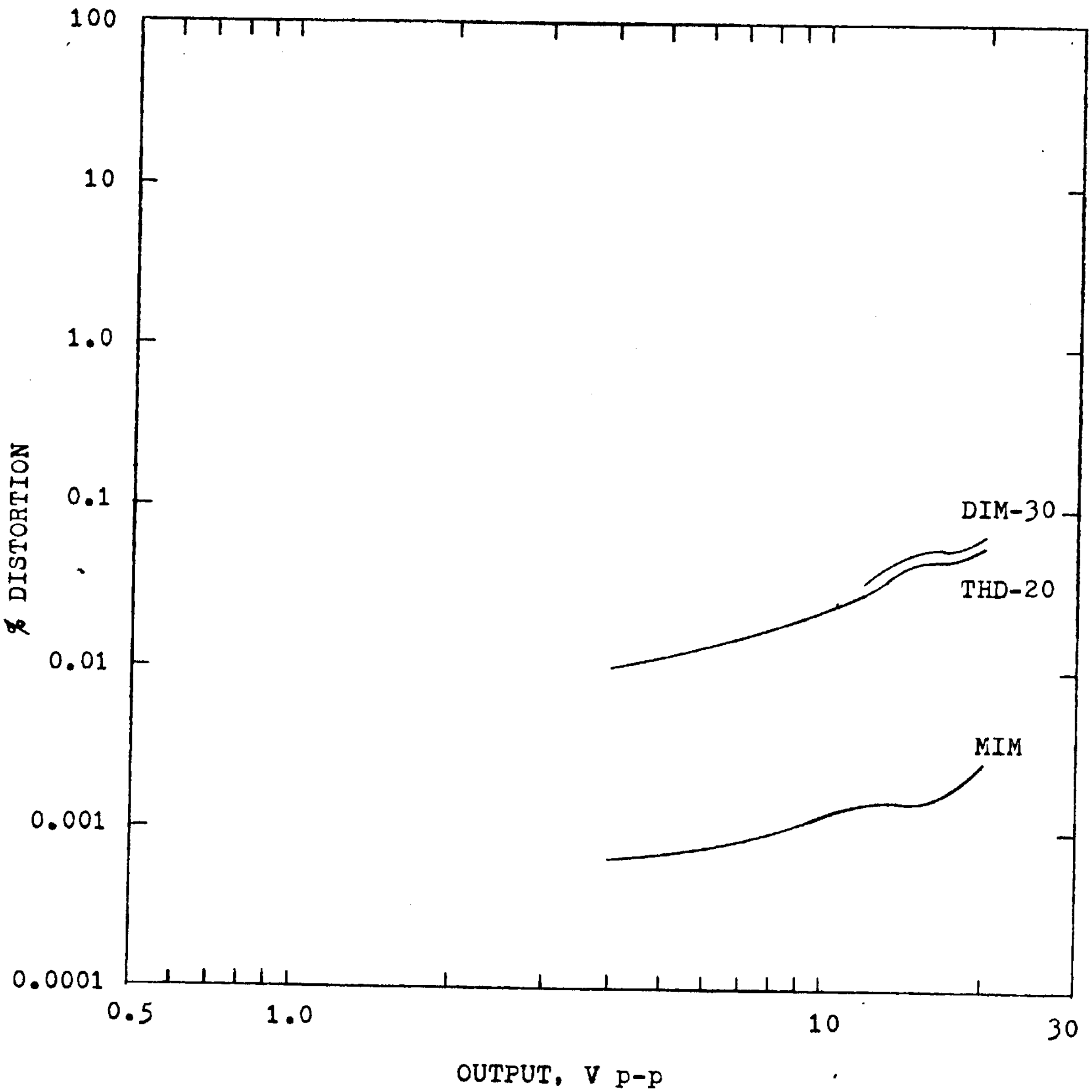


FIGURE 12: Distortion characteristics for a 748 operational amplifier externally compensated with 2 pF and operated at an inverting gain of 10.

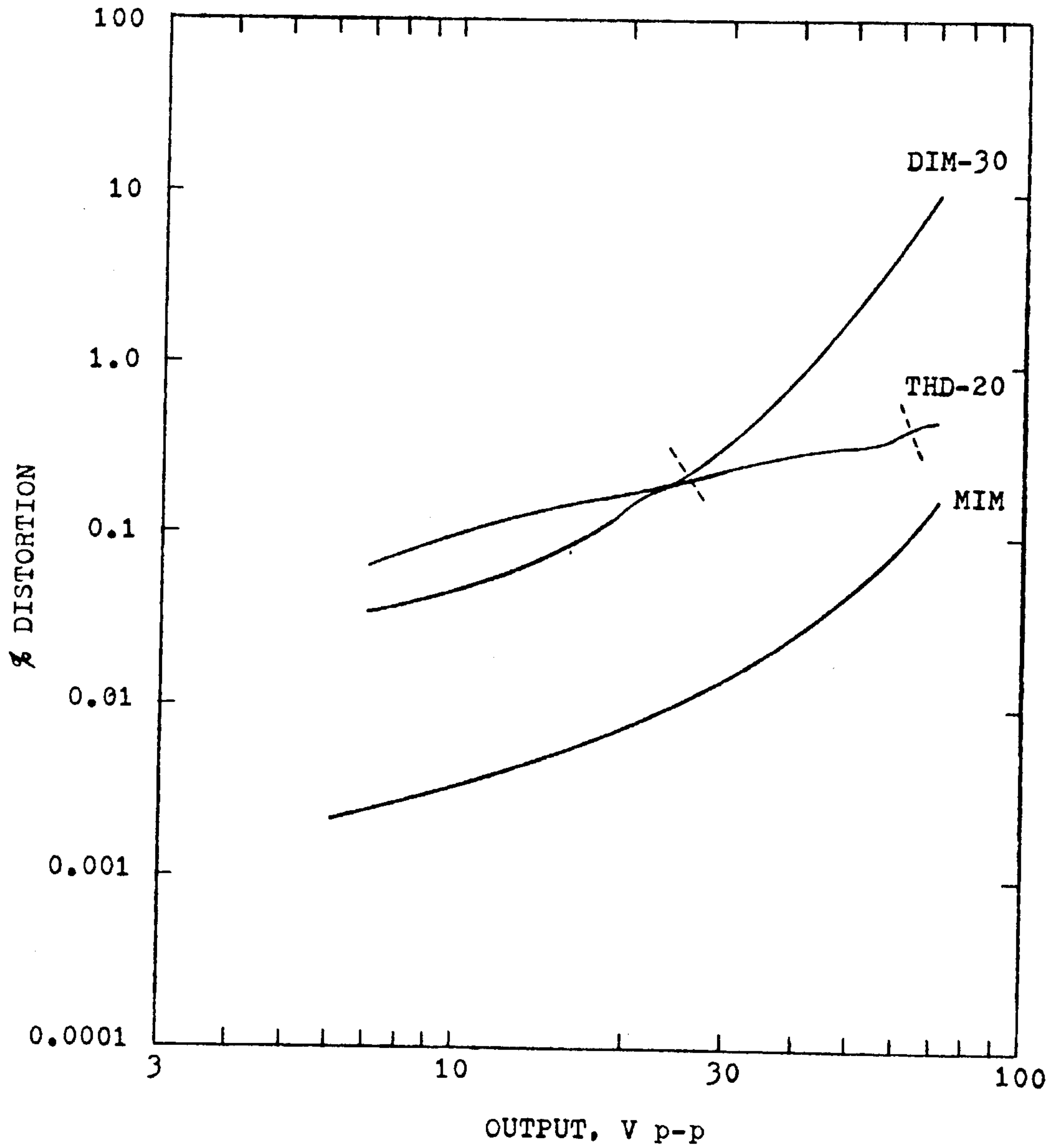


FIGURE 13: Distortion characteristics for a 70-watt power amplifier with substantial TIM.