REVIEW OF FREQUENCIES AND LEVELS FOR DIGITAL AUDIO PERFORMANCE MEASUREMENTS

2223 (A-5)

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Presented at the 78th Convention 1985 May 3-6 Anaheim

AN AUDIO ENGINEERING SOCIETY PREPRINT

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ABSTRACT

This paper evaluates a wide variety of test frequencies and levels at which digital audio linearity and steady state distortion measurements can be performed. The number of unique codes needed to synthesize the test signals are calculated, and the resulting sensitivity of the sequences to pinpointing DAC random errors are shown. Test sequences for consumer (CD) equipment operating with 44.1kHz and professional systems using 48kHz sample frequencies are examined.

SUMMARY

A study was conducted to provide guidelines for the selection of frequencies and levels at which compact disc player linearity or steady state distortion measurements should be performed. The general nature of the study makes the results easily applicable to the evaluation of professional equipment (ie. digital audio tape recorders). Computer synthesized test signals having frequencies which are relatively prime numbers with respect to the sample frequency are recommended, although the more commonly used frequencies such as those stated in ISO (266-1975) are probably acceptable for normal CD player evaluation. For

testing of professional equipment operating with the AES recommended sampling frequency of 48kHz, use of the ISO preferred test frequencies may give misleading results. In covering the region from -70db to -95db test signals at the reference frequency in steps of -5db would be preferred, although steps of -10db ending at -90db are probably adequate.

0 INTRODUCTION

Performance measurements of digital audio systems require greater care than their more familiar analog counterparts. This is especially true at the lower signal levels, where nonlinearity and distortion begin to increase for linearly encoded PCM audio. At present there exist more than a half dozen compact disc (CD) test discs. These excellent evaluation tools comprise a wide variety of formats and signals [1,2,3]. This report compares some advantages and disadvantages of various test signals in the evaluation of CD players. It addresses these points on a theoretical basis by providing computed spectra of digitally synthesized test signals and simulation of simple DAC nonlinearities.

The report attempts to provide to those interested in performing CD player measurements an insight into what could be expected in typical real data (ie. the limits) and some possible ways of interpreting results. In this regard concentration is placed on traditional performance indicators such as linearity, THD and THD+N. Tables of these values as a function of frequency and level should be useful to those who wish to use signals generated by digital audio components such as CD as a good quality analog signal source for testing other equipment. Although it is beyond the scope of this study to elaborate on other less conventional testing techniques, the reader should be aware that there exist a variety of procedures that are designed to measure performance of digital components more rigorously, and to give better diagnostic indications of problems [4].

Because of the rather general nature of the study and the way the material is presented, those concerned with professional equipment should find this information to be of use. It is further hoped that this report will provide assistance to those in the process of implementing future generations of test discs. In this latter regard the present paper is a direct result of a contribution circulated within the CD Player Subcommmittee of the EIA, which is actively concerned with this topic [5]. Those aware of the original document should recognize that the present version has been much expanded, more convenient references provided in some calculations, and several minor text errors corrected. As an example, values of THD+N have been added along with the previously presented values of THD, and both have been normalized to the total power of the quantized signal. This permits easy comparison between different traditional performance measures, and future correlation with experimental data using existing laboratory equipment. The conclusions and recommendations are those presented by the author, and should not be necessarily viewed as an opinion of the committee.

1 TEST SIGNAL SEQUENCE

In a linear PCM digital audio system the data codes representing time sequential samples of a sinusoidal signal are determined by the peak amplitude, the signal phase, the number of quantizing bits, and the sample frequency. In any sequence some codes are repeated very often, others less so, and still others possibly never. The statistical distribution of the codes can be significantly different than the corresponding amplitude distribution of the analog waveform. Here when we speak of data codes [6], or simply codes, we refer to the integer equivalent of the bit pattern.

To see how the number of different codes used in a synthesis is dependent upon amplitude and duration we should remember that in 16 bit implementations an unclipped full scale symmetric waveform (eg. a 0db sinusoid) of very long duration could have codes ranging from 32767 through -32767, or a total of 65535 possible unique values (this includes the 0 code). The number of unique codes can not exceed twice the full scale code value plus one; or the number of samples to be synthesized, which ever is least. Sinewaves below -80db re maximum use only a few codes no matter what amplitude or frequency is desired. For example, Figure 1 shows how a level of -90db is represented by a sequence of 1's, followed by a sequence of 0's, followed by a sequence of -1's. No other code values are possible. When this situation occurs, different test amplitudes and frequencies are characterized by different amounts of time that each code level is turned on or off, a type of duty cycle. A code sequence of all zeros (ie. 0, 0, 0...) represents an idle channel, or a signal with peak amplitude below one half LSB before quantizing.

In cases where the sample frequency and the test frequency are related by small integer ratios, such as 48kHz and 3kHz, only a small number of unique codes are required to synthesize the signal for any amplitude, even full scale. Owing to the periodic nature of the signal and sample frequencies, exactly an integer number of samples sometimes corresponds to an integer number of signal periods. If the DAC were nonlinear at these frequently used code values, results from distortion measurements might be very high. If on the other hand, the DAC were perfect at these code values but nonlinear at others, the distortion measurement results might be exceedingly low. In either case the results might not provide a balanced evaluation of the DAC for normal audio waveforms. It becomes quickly apparent that signals synthesized with relatively short periodic code sequences might present serious problems in the system evaluation process if used without caution. Some suppliers of CD test discs use test frequencies such as 997Hz or 1001Hz to avoid some of these and other related difficulties [2,1].

2 DAC MODEL

As the idealized DAC and its accompanying circuitry receive the various codes it converts these data to a voltage which is held constant until the next sample period and change of code. An ideal low pass filter then removes the spectral components above the Nyquist Frequency to smooth the final output waveform [7]. The ideal DAC transfer function would appear as a staircase with uniform step size (Figure 2). Real DACs are not ideal and different implementations will show preference to different forms of nonlinearity [8].

It is not the purpose of this study to model all DAC deficiencies, so that in discussing DAC nonlinearities only isolated nonuniformities in the output step size of the device are being considered. The magnitude, referred to here as the Error Ratio, is the error in the voltage output of the DAC during conversion of a code when the error is normalized to the minimum positive voltage change, 1 LSB, in the ideal DAC of equal precision. Thus if the minimum voltage change of the ideal DAC for each step were 1.0 microvolt, then an Error Ratio of -0.5 would mean a voltage output of 0.5 microvolts less than required at that step location. An error of -1.0 would mean a missing code or a voltage change of 0.0 microvolts from the next lowest code. An error of -1.5 would correspond to a nonmonotonic DAC whose output would be 1.5 microvolts less than required when converting that code.

The essentially static errors differ from those associated with deficiencies in the multiplexing and deglitching circuitry of some implementations. These latter dynamic errors which are of equal importance have not been modeled in this paper. Care has to be taken in the use of present test discs in that some are configured with both channels on at the same time, and others with only one. This situation can result in differences in measurement performance due to dynamic DAC errors. This would tend to suggest that agreement on test signal format, possibly to include both single and dual channel sequences, might be helpful and important.

3 TEST FREQUENCIES

Tables 1 and 2 depict the number of codes used to synthesize various sinusoidal test signals with two different standard sample frequencies. Three durations of approximately one, ten and 100 waveform periods were chosen to illustrate the trends. These correspond to about 1ms, 10ms and 100ms respectively for a test signal of 1kHz nominal frequency. It should be noted that it is sometimes possible to change the actual codes and the number of unique codes by altering the initial signal phase; only the zero phase condition has been presented.

Notice in particular that for the CD sample frequency of 44.1kHz the entries for 1kHz and 997Hz are either the same or are very close for amplitudes at and below -50db. In addition, the number of codes used is either identical or nearly so to the number of possible codes for these test frequencies and levels. At durations more than 10ms and levels higher than -50db the data begin to differ. A 1kHz test signal at -30db would use only 423 codes, as compared with 2018 codes for 997Hz during a 100ms synthesis. Note that with a sample frequency of 44.1kHz, a test signal of 1kHz has a periodic sequence of codes which repeat in exactly 441 samples comprising exactly 10ms. Under these conditions a duration of 100ms is composed of 10 such periodic sequences, and produces no further unique codes.

In the case of 48kHz sample frequency the situation is more acute. For any amplitude from about -60db to 0db, only 25 unique codes are required to represent the 1kHz test signal for durations of 1ms to 100ms. With so few codes needed for synthesis, measurement results from different DACs might vary greatly even though overall audio performance might be approximately equivalent. A comparison of Table 1 and 2 for 997Hz shows that about the same number of codes is employed during synthesis with either the 48kHz or the 44.1kHz sample frequencies.

An important implication to be noted from the previous tables is that any major differences in performance results which are solely due to the choice of test frequencies are likely to manifest themselves at higher rather than at lower levels. At -70db and below, all of the test frequencies require almost the same number of unique codes and are represented by almost identical sequences. At the higher levels the spectral purity of the test signals in terms of the total quantizing error approximated by THD+N varies slightly with the number of unique codes. What is rather different is the spectral distribution of error, shifting between regions near the harmonic ratios (THD) and other areas of the spectrum. Tables 3 and 4 illustrate these points and provide a theoretical bound for player performance. Actual CD player measurements of THD+N are within 5dB of these theoretical values from a level of -10dB down to -90dB.

One must use considerable care when interpreting THD measurements at these higher signal levels. The term THD is used here rather loosely to designate the spectral energy in neighborhoods centered around harmonic ratios of the test signal. This is analogous to a narrow-band spectrum analysis. The actual spectrum does not always appear to exhibit harmonic character. The spectrum of test signals related to the sample frequency by integer values, such as 1kHz sampled at 48kHz, do have the energy from the quantizing process concentrated in components located at harmonic ratios. In other situations, such as 1kHz or 997Hz sampled at 44.1kHz, the spectrum appears very random, and a harmonic like character is not noticable until about -65dB. Even at this level, the spectrum does not have only one, but has several components clustered near the harmonic ratios and above the background. In the case of 44.1kHz sample frequency, there is a slight difference in the character of the spectra produced by 1kHz versus 997Hz test signals, in that the components of the former cluster more closely. Because of the nature of the spectrum, there is a slight variation as a function of analysis length in the values of THD for 997Hz, but not for 1kHz.

The reader should always keep in mind that different test signals will have different spectral characteristics depending upon the degree of error correlation between the samples [7]. The reason THD values have been presented and spectra discussed is that identification of the character of distortion, particularly the presence of discrete components is very important in the evaluation of a digital system. Unfortunately, results from traditional tests can be difficult to interpret unless one is aware of what should be expected when using the various available test signals. A relative comparison of performance between different players with different test signals must take these facts into account.

Tables 5A and 5B depict a selection of various frequencies normally used or proposed for testing of analog and digital equipment. The tables show the number of unique codes needed to synthesize the test signals at 44.1kHz and 48kHz sample frequencies, and whether the signal frequency is a prime number [9]. Based on the above discussion it is clear that some of these frequencies should be examined more carefully before approval for arbitrary use in general testing. Certain test frequencies which might present difficulties at 44.1kHz might be acceptable at 48kHz and vice versa. Also some test frequencies might not be recommended for use at either sample frequency, and still others might be acceptable for both. Note that this latter category comprises all of the prime numbered frequencies and many others which are not prime. The important consideration is not whether the test frequency is prime, but that the number of common factors between the test signal and sample frequency be a minimum, preferably zero (ie. relatively prime).

From this list, particularly poor values for testing equipment operating with 44.1kHz might be 315Hz, 3kHz, 6kHz, 7kHz and 18kHz. The other commonly used frequencies which include many ISO preferred frequencies [10], such as 50Hz, 100Hz, 200Hz, 500Hz, and all multiples of 1kHz would probably not be as good as the prime or relatively prime listings. It is also interesting to note that 6301Hz and 6367Hz are both prime numbered frequencies using approximately the same number of codes, the former uses slightly more codes in 100ms and less in 10ms than the latter.

The number of unique codes listed for each proposed test frequency gives an indication of suitability or unsuitability, but it does not provide a quantitative measure of the sensitivity of THD+N results to the position of DAC code errors. In order to place the findings in Table 5 in proper perspective it is necessary to examine the resulting DAC distortion as might be indicated by the different test signals. Using Table 5 as a guide 997Hz, 1kHz, 3kHz, 3163Hz were examined for both 44.1kHz and 48kHz sample frequencies. In addition 315Hz and 317Hz were also included for the 44.1kHz condition.

Simulations of random DAC nonlinearity of the type previously described were conducted. These consisted of maintaining the quantity and magnitude of the error constant and varying the location of the errors in each trial. For these purposes a uniform distribution of approximately 10% of the total available codes or 6550 errors, and three error magnitudes (Error Ratio) of 0.0, -0.5, and -1.2 were assumed. The maximum, minimum, mean, and maximum deviation in THD+N based on six different simulations of error locations for each frequency and error magnitude were computed. The Error Ratio of 0.0 indicates a perfect, error free DAC.

The purpose of this procedure is to determine how much variation in the measurement of THD+N might be expected with only a small change in the test frequency, and to observe any patterns in the resulting output data. From the previous discussion it might be expected that the test frequencies employing the greatest number of unique codes would have the least variation trial to trial providing a reliable estimate insensitive to error location. Some variation in THD+N is necessary since each simulation represents similar but not identical DACs. Test sequences employing the fewest unique codes are likely to have the widest variation in THD+N. It might also be expected that at the lower levels, about -70db, where all the test frequencies employ the same number of codes the results will converge for each condition.

Examination of Tables 6 thru 10 confirm the above expectations. Taking the results for 48kHz sample frequency first, Table 6 and 7 indicate that when the prime numbered test frequencies of 997Hz and 3163Hz are used less variation in THD+N occurs. The worst deviations shown are from Table 7 for testing with 3kHz, at levels of either 0.0db or -20db. Under these simulated conditions the maximum deviation from the mean for the Error Ratio of -0.5 was 3.9db and -3.2db respectively. The corresponding results for 3163Hz were 0.1db and 0.2db. With an Error Ratio of -1.2 the maximum deviations at 3kHz were even greater than the previous, being 4.9db and -6.5db. The results with 3163Hz for this Error Ratio were found to be -0.2db and 0.4db at the test levels previously indicated. Results with 1kHz and 997Hz are similar and are about half the previously stated values at all the Error Ratios and levels mentioned.

For 44.1kHz sample frequency the results depicted in Tables 8 thru 10 show exactly the same trends as for 48kHz, but fortunately for CD testing they are not nearly so severe. In general the maximum deviations are less than one quarter of those illustrated in the corresponding conditions of the 48kHz examples. The worst case occurs with a 3kHz test frequency at 0db, where the maximum deviation was -1.3db as compared with -0.2db for 3163Hz. At the important test reference frequency of 1kHz the maximum deviation was 0.6db, compared with 0.1db for 997Hz. The results at 315Hz and 317Hz were slightly better than at 3kHz and 3163Hz, but not quite as good as at 1kHz and 997Hz.

The previous analysis presented data only on THD+N partly because only uniformly distributed random DAC errors were being considered. If the DAC model included systematic nonlinearities and different random error distributions, example clusters, the maximum deviations for the ISO frequencies would have almost certainly been greater. In addition, results would have been presented which included variation of THD, and possibly some other measure which emphasize components correlated with the test signal and sample frequencies. As previously noted from Tables 3 and 4, there is a difference in the spectral balance of the residual distortion carried by the quantized test signal. It might be expected that the prime numbered test frequencies, because of their much lower values of THD, might be somewhat more useful or illustrative in picking out small amounts of correlated DAC distortion. As pointed out earlier, interpretation of THD and the signal spectrum can be complex, so this possibility may not be easily realized.

There are many other considerations besides the number of codes used in a synthesis. These would include examination of other kinds of nonlinearities which might be expected in the digital section, and of course the equally important analog portion. In addition, the capabilities of practical test equipment, and the range of future player performance must also be taken into account. In any event, the uniformity of procedures as to the choice of test frequencies would seem to be an important goal.

4 TEST LEVELS

In the previous section it was shown how the number of codes used during a digital synthesis of a sinusoidal waveform was a function of a number of different parameters including the test signal frequency and system sample frequency. To minimize adverse sensitivity of results to the position of DAC nonlinearities the choice of test frequency was made on the basis of maximizing the number of unique codes used in synthesizing the signal. This procedure was primarily conducted to improve reliability of THD, and THD+N measurements at high and medium signal levels (ie. those at and above about -60db). Checking performance at lower signal levels where the number of unique codes exercised is very few requires further consideration. For PCM audio this region is very important because even relatively minor DAC errors can cause appreciable increases in audible distortion [8]. To guard against misjudgments or to permit more detailed diagnostics, careful concern must be given to establishing appropriate levels at which measurements are to be conducted.

Although the recommendation of the previous section was for a reference frequency of 997Hz, all data presented in this section are based on 1kHz. Most test discs currently use this value so the information was felt to be of wider benefit. In addition, the results in terms of THD and THD+N at 997Hz were found to differ very little from those of 1kHz at the low test levels and types of DAC nonlinearities considered in this section. Where the spectra were not the same it was usually in the magnitude of the lower level components. All the examples shown are for the sample frequency of 44.1kHz, but the results are very similar for 48kHz.

Table 11 provides in some detail how linearity and distortion vary as a function of level from -70db to -96db in -1db steps. Also included are the number of codes used by the DAC during 160ms of operation (7056 samples). As the test signal amplitude decreases, fewer and fewer codes are used in the synthesis, and the waveform takes on the appearance of a staircase with fewer steps of longer duration. Finally when the amplitude drops to a level where only three codes are used, the staircase has three steps with more and more time spent using the zero code. The previously mentioned Figure 1 is an illustration of this process.

It is apparent that poorer and poorer approximations to the ideal sinewave will result in spectra with very strong harmonic character. Table 12 depicts the relative harmonic spectra of the 1kHz test signal at amplitudes from -60db to -95db in steps of -5db. Note from Table 12 that in all the spectra presented the even harmonics (ratios of 2,4,6...) are lower in relative level to the odd harmonics (ratios of 1,3,5...). Also the distortion in the harmonics as measured by THD increases somewhat more rapidly than the change in signal level or the increase in THD+N. Both of these measures converge at low signal amplitudes. In addition to the expected higher distortion, a linearity error at the lower test amplitudes is predicted even for a system having an ideal DAC and low pass filter.

Since the amplitudes of -90db and -95db use only the three codes of 1, 0, and -1 during synthesis, any DAC nonlinearity effecting -95db will be readily observable at -90db. In practical testing the more favorable signal to noise ratio at -90db would probably make any DAC error more easily measurable at this slightly higher amplitude.

Table 13 depicts the effect on the -90db signal spectra of a DAC with varying amounts of nonlinearity. Only the first 10 spectral components are shown, but total harmonic distortion was computed on the full 21 components as previously illustrated. The table was developed by assuming that the indicated amount of error existed in the conversion of code level 1 (the LSB). From the results it is clear that not only does the level of the fundamental change and the harmonic content increase, but there is a strong change in the balance of the harmonics. The level of the even ordered harmonics, especially the second and fourth become very noticeable. This fact might be useful as a diagnostic tool in debugging digital audio systems. Note from the data that there is a greater increase in THD+N than THD. This is caused by a large increase in DC due to the isolated and noncomplementary nature of the DAC nonlinearity, ie. the waveform is asymmetric.

Table 14 shows how this type and location of error changes the measurement of linearity, distortion and harmonic spectra as a function of signal amplitude. A relatively large error ratio of -1.2 along with the ideal ratio of 0.0 are shown in the table for the levels of -95db, -90db, -80db, and -70db. Even at -70db where 21 codes are needed to represent the signal, the error in code value 1 is detectable as a significant increase in the second harmonic (29db), and in the total harmonic distortion (4.7db). The value of THD+N increases as well, but not nearly so much (2.0db). Due to other sources of distortion, this nonlinearity might be easily overlooked during testing at -70db, particularly if only THD+N were observed. On the other hand, depending upon overall system noise level it would be very apparent at -80db and below. Other system defects may also cause an increase in the even harmonics, so caution in interpreting results is always in order.

It is also important to understand how a similar type of error located at a different DAC code might cause changes in linearity and distortion. Table 15 shows this relationship for -70db and -60db where the code value 10 was generated with the same error voltage as Table 14 (-1.2 Error Ratio). A code value of 10 corresponds to the highest code needed in generating a level of -70db. Also keep in mind that 67 codes are required to represent -60db, as compared with 21 for -70db. The error is clearly visible in the spectrum at -70db, and in the measures of distortion; an increase of 10.5db in THD, and 4.8db in THD+N. From the data it would appear very doubtful that practical measurements at -60db would reveal any problems, and certainly measurements below -70db would not. The latter statement is true by merely observing that signals below -70db do not use the code at level 10 during DAC operation.

The code value of 10 was chosen as an illustration, and probably represents the worst position (ie. maximum nonlinearity) for synthesis of the -70db sinewave. Thus the example is possible in practice, but might be judged rather extreme. It is also intended to point out that a single or maybe even a few random code errors at higher DAC locations are less of a problem in terms of performance than if the errors existed at lower locations [8]. At higher levels the errors represent a smaller fraction of codes used during DAC operation. The reader should refer back to the discussion on test frequencies where many errors were simulated over the entire DAC range.

5 METHOD OF ANALYSIS

This section discusses the analytical approach, in particular the method used to generate the test signals, the FFT spectrum analysis, and the values of distortion. The signals were synthesized on a VAX 11/780 in VAX FORTRAN with all variables and functions declared as double precision. This arrangement provided about 16 digits of significance [11] and was very useful in determining the number of unique codes employed to represent the signal during long time sequences. Signal durations of approximately one to several hundred milliseconds, comprising a few to many thousands of points were synthesized. The spectra shown were computed using a 7056 point, zero padded Blackman-Harris window with 92db side lobe attenuation, and a single precision floating point Singleton type FFT algorithm [12]. Since the distortion spectrum was derived from analyzing the time sequence of the quantizing error, double precision FFT computation was not felt to be necessary.

Spectral components at each harmonic are presented as a level in decibels relative to the fundamental. The total power in the quantized signal (TOTAL), and the level of the fundamental (FUND.) relative to the power in a full scale (0.0db) signal were calculated. These values serve as different measures of linearity. Two quantities were computed as values relative to the total power of the quantized signal: 1- the total power in the harmonics less the fundamental (THD), and 2- the total power of the quantizing error less the spectral component at the fundamental (THD+N). The procedure for computing these latter two quantities is shown in the block diagram of Figure 3. The calculated values of THD do not include the last harmonic in the ideal pass band whether it is located at the Nyquist frequency of just before it. The normalization of results was performed in accordance with EIA Interim Standard CPIS-2 [13].

As an illustration of the basic method used in the study, Figure 4 depicts part of a sinusoidal type waveform being quantized to three bits precision (sign magnitude with MSB left and LSB right). In this representation the decision (switching) level is set for one half LSB which is included as part of the next higher code. Thus a voltage value of 0.5 exactly would be encoded as 1 (001), 1.5 exactly as 2 (010), 2.5 exactly as 3 (011), and 3.5 exactly would be out of range and require more bits precision. Negative values would be encoded similarly. Thus -0.5, -1.5, -2.5, -3.5 would be encoded as -1 (101), -2 (110), -3 (111), and -4 (not encoded) respectively.

A value of 3.499... then becomes the peak amplitude of the largest sinusoidal signal still within 1/2 LSB of a legal code. This peak value could be used as the reference when generating signals with amplitudes stated in decibels. An alternative value of 3.000... could also be chosen as the reference. The advantage of employing this second form is that the peak value of the signal at zero db (0.0db) now corresponds exactly to the maximum code value with zero (0.0) quantizing error. This latter choice of reference was employed in the study, so that 32767.0 in double precision was used as the full scale amplitude value when generating overall levels in dB. If the former value were employed, some slight differences in the number of unique codes at the various levels will result.

6 CONCLUSIONS AND RECOMMENDATIONS

For purposes of testing distortion of both analog and digital portions of an unfamiliar digital audio system the following frequencies based on prime numbers are recommended for obtaining the most reliable results:

19Hz, 41Hz, 101Hz, 317Hz, 499Hz, 997Hz, 3163Hz, 6301Hz, 10007Hz, 16001Hz, 19001Hz, and 19997Hz. The frequency of 997Hz should be chosen as the test frequency for detailed linearity and distortion tests. This frequency set has the advantage that it can be used for both consumer products, such as CD, and professional equipment even though the sample frequencies are different in each case.

Based on the previous discussion a full complement of frequencies for the purpose of distortion measurements should be provided at 0db and somewhere between -20db and -30db, the exact location is rather arbitrary. The value of -25db is used for convenience and is intended to provide evaluation at a level corresponding more closely to normal recording and listening practice. At the recommended reference frequency of 997Hz, signals for linearity or distortion measurements should be provided from 0db down to -70db in steps of -10db. Many test discs presently provide several additional points between 0db and -10db. Any choice will be somewhat arbitrary, the values -1db, -3db, -6db seem to be most commonly preferred. In the lower range from -70db down to -95db, increments of -5db would provide useful but not necessarily essential information. Increments coarser than -10db should be discouraged.

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TIME		1MS		10MS		100MS	
SAMPLES		44		441		4410	
FREQ (Hz)	LEVEL (DB)	CODES USED	CODES	CODES USED	CODES	CODES USED	CODES
	0	44	44	441	441	441	4410
	-10	44	44	441	441	441	4410
	-20	44	44	437	441	437	4410
	-30	44	44	423	441	423	2073
1000	-40	44	44	381	441	381	657
	-50	39	44	209	209	209	209
	-60	30	44	67	67	67	67
	-70	19	21	21	21	21	21
	-80	7	7	7	7	7	7
	-90	3	3	3	3	3	3
	0	44	44	441	441	4340	4410
	-10	44	44	440	441	4193	4410
	-20	44	44	434	441	3672	4410
	-30	44	44	416	441	2018	2073
997	-40	44	44	343	441	657	657
	-50	44	44	191	209	209	209
	-60	35	44	67	67	67	67
	-70	20	21	21	21	21	21
	-80	7	7	7	7	7	7
	-90	3	3	3	3	3	3

TABLE 1. Number of Unique Codes Used and Possible for Test Signals Sampled at 44.1kHz and 16 Bits Precision.

TIME		1MS		10MS		100MS	
SAMPLES		48		480		4800	
FREQ (Hz)	LEVEL (DB)	CODES USED	CODES	CODES USED	CODES	CODES USED	CODES
	0	25	48	25	480	25	4800
	-10	25	48	25	480	25	4800
	-20	25	48	25	480	25	4800
	-30	25	48	25	480	25	2073
1000	-40	25	48	25	480	25	657
	-50	25	48	25	209	25	209
	-60	23	48	23	67	23	67
	-70	19	21	19	21	19	21
	-80	7	7	7	7	7	7
	-90	3	3	3	3	3	3
	0	48	48	480	480	4697	4800
	-10	48	48	476	480	4482	4800
	-20	48	48	465	480	3824	4800
	-30	48	48	435	480	2073	2073
997	-40	47	48	347	480	657	657
	-50	41	48	208	209	209	209
	-60	32	48	67	67	67	67
	-70	10	21	21	21	21	21
	-80	7	7	7	7	7	7
	-90	3	3	3	3	3	3

TABLE 2. Number of Unique Codes Used and Possible for Test Signals Sampled at 48kHz and 16 Bits Precision.

FREQ (Hz)	LEVEL (DB)	TOTAL (DB)	FUND. (DB)	THD (DB)	THD (%)	THD+N (DB)	THD+N (%)	CODES
	0	0.0	0.0	-107.6	0.00042	-97.8	0.0013	441
	-1	-1.0	-1.0	-106.7	0.00046	-96.8	0.0014	441
	-3	-3.0	-3.0	-103.9	0.00064	-95.3	0.0017	441
	-6	-6.0	-6.0	-101.9	0.00080	-92.3	0.0024	441
	-10	-10.0	-10.0	-95.2	0.0017	-87.9	0.0040	441
	-12	-12.0	-12.0	-96.4	0.0015	-86.8	0.0046	441
1000	-20	-20.0	-20.0	-87.6	0.0042	-77.9	0.013	437
	-24	-24.0	-24.0	-84.9	0.0057	-73.6	0.021	431
	-30	-30.0	-30.0	-78.7	0.012	-68.1	0.039	423
	-40	-40.0	-40.0	-68.0	0.040	-58.0	0.13	381
	-50	-50.0	-50.0	-60.7	0.092	-47.9	0.40	209
	-60	-60.0	-60.0	-48.6	0.37	-38.0	1.3	67
	-70	-70.1	-70.1	-36.2	1.5	-28.3	3.8	21
	0	0.0	0.0	-110.8	0.00029	-98.1	0.0012	6888
	-1	-1.0	-1.0	-110.2	0.00031	-97.1	0.0014	6860
	-3	-3.0	-3.0	-109.9	0.00032	-95.1	0.0018	6816
	-6	-6.0	-6.0	-107.7	0.00041	-92.1	0.0025	6703
	-10	-10.0	-10.0	-101.4	0.00085	-88.0	0.0040	6506
	-12	-12.0	-12.0	-98.9	0.0011	-86.1	0.0050	6342
997	-20	-20.0	-20.0	-92.4	0.0024	-78.1	0.012	5089
	-24	-24.0	-24.0	-87.5	0.0042	-74.1	0.020	3942
	-30	-30.0	-30.0	-81.7	0.0082	-68.1	0.039	2073
	-40	-40.0	-40.0	-73.4	0.021	-58.0	0.13	657
	-50	-50.0	-50.0	-60.3	0.097	-47.9	0.40	209
	-60	-60.0	-60.0	-50.0	0.32	-38.0	1.3	67
	-70	-70.0	-70.1	-36.2	1.5	-28.3	3.8	21

TABLE 3. Theoretical Linearity and Distortion of High Level Test Signals Sampled at 44.1kHz and 16 Bits Precision With a Time Duration of 160ms (7056 samples).

FREQ (Hz)	LEVEL (DB)	TOTAL (DB)	FUND. (DB)	THD (DB)	THD (%)	THD+N (DB)	THD+N (%)	CODES
	0	0.0	0.0	-98.0	0.0013	-97.8	0.0013	25
	-1	-1.0	-1.0	-99.5	0.0011	-99.5	0.0011	25
	-3	-3.0	-3.0	-95.0	0.0018	-95.0	0.0018	25
	-6	-6.0	-6.0	-91.7	0.0026	-91.7	0.0026	25
	-10	-10.0	-10.0	-89.5	0.0033	-89.5	0.0033	25
	-12	-12.0	-12.0	-87.1	0.0044	-87.1	0.0044	25
1000	-20	-20.0	-20.0	-79.7	0.010	-79.7	0.010	25
	-24	-24.0	-24.0	-75.4	0.017	-75.4	0.017	25
	-30	-30.0	-30.0	-69.2	0.035	-69.2	0.034	25
	-40	-40.0	-40.0	-59.1	0.11	-59.1	0.11	25
	-50	-50.0	-50.0	-49.5	0.33	-49.5	0.33	25
	-60	-60.0	-60.0	-37.3	1.4	-37.3	1.4	23
	-70	-70.1	-70.1	-29.2	3.5	-29.2	3.5	19
	0	0.0	0.0	-110.2	0.00031	-98.1	0.0012	6773
	-1	-1.0	-1.0	-110.6	0.00030	-97.0	0.0014	6730
	-3	-3.0	-3.0	-106.8	0.00046	-95.0	0.0018	6665
	-6	-6.0	-6.0	-105.4	0.00041	-92.1	0.0025	6522
	-10	-10.0	-10.0	-101.6	0.00054	-88.1	0.0039	6136
	-12	-12.0	-12.0	-99.7	0.0010	-86.1	0.0050	5883
997	-20	-20.0	-20.0	-93.3	0.0022	-78.1	0.012	4323
	-24	-24.0	-24.0	-86.2	0.0049	-74.1	0.020	3447
	-30	-30.0	-30.0	-81.0	0.0089	-68.2	0.039	2073
	-40	-40.0	-40.0	-71.2	0.028	-58.0	0.13	657
	-50	-50.0	-50.0	-59.0	0.11	-47.9	0.40	209
	-60	-60.0	-60.0	-48.7	0.37	-38.0	1.3	67
	-70	-70.0	-70.1	-35.8	1.6	-28.3	3.8	21

TABLE 4. Theoretical Linearity and Distortion of High Level Test Signals Sampled at 48kHz and 16 Bits Precision With a Time Duration of 147ms (7056 samples).

RATE		44.1KHZ		48KHZ	
TIME		10MS	100MS	10MS	100MS
SAMPLES		441	4410	480	4800
FREQ(Hz)	PRIME	CODES	CODES	CODES	CODES
19	YES	441	2711	480	3835
20	NO	441	2055	480	1157
31	YES	402	2796	418	2709
31.5	NO	344	687	398	3099
40	NO	419	2055	296	591
41	YES	413	3127	457	3244
50	NO	219	437	238	475
53	YES	348	3628	462	2998
61	NO	434	3009	471	3202
63	YES	264	347	429	3481
100	NO	437	437	239	239
101	YES	425	3346	469	2577
125	NO	436	859	193	193
127	YES	428	3067	429	3906
199	YES	407	3010	427	3825
200	NO	437	437	121	121
250	NO	221	437	97	97
251	YES	432	3080	469	3329
315	NO	71	71	469	1523
317	YES	427	3277	463	3382
400	NO	437	437	61	61
401	YES	414	3777	433	3103
499	YES	435	3052	473	2910
500	NO	437	437	49	49
997	YES	435	3672	465	3824
1000	NO	437	437	25	25
1001	NO	437	2575	474	3904
1999	YES	435	3752	455	3599
2000	NO	437	437	13	13

TABLE 5A. Number of Unique Codes Used for Various -20db Test Signals Sampled at 44.1kHz or 48kHz and 16 Bits Precision.

RATE		44.1KHZ		48KHZ	
TIME		10MS	100MS	10MS	100MS
SAMPLES		441	4410	480	4800
FREQ(Hz)	PRIME	CODES	CODES	CODES	CODES
3000	NO	147	147	9	9
3149	NO	441	3163	472	3097
3163	YES	435	3662	474	3232
4000	NO	437	437	7	7
4001	YES	387	3651	416	3029
4999	YES	431	3201	474	3815
5000	NO	437	437	25	25
6000	NO	147	147	5	5
6301	YES	407	3643	391	3893
6367	YES	423	3167	470	3868
7000	NO	63	63	25	25
7001	YES	429	3599	474	2007
7993	YES	428	3079	480	3420
8000	NO	437	437	3	3
9999	NO	435	2265	455	3156
10000	NO	437	437	13	13
10007	YES	432	2378	473	3315
12500	NO	437	437	49	49
12503	YES	418	3485	332	2689
15999	NO	427	3044	367	2949
16000	NO	437	437	3	3
16001	YES	427	3288	366	2009
17999	NO	431	3548	376	3170
18000	NO	49	49	5	5
18013	YES	431	3089	471	3893
19000	NO	437	437	25	25
19001	YES	437	1649	474	3806
19997	YES	433	2919	468	3247
19999	NO	420	2574	316	3655
20000	NO	437	437	7	7

TABLE 5B. Number of Unique Codes Used for Various -20db Test Signals Sampled at 44.1kHz or 48kHz and 16 Bits Precision (Continued)

ERROR	LEVEL DB	MAXIMUM 1000	MAXIMUM 997	MINIMUM 1000	MINIMUM 997	MEAN 1000	MEAN 997	MAX DEV 1000	MAX DEV 997
	0	-97.8	-98.1	-97.8	-98.1	-97.8	-98.1	0.0	0.0
	-20	-79.7	-78.1	-79.7	-78.1	-79.7	-78.1	0.0	0.0
0.0	-40	-59.1	-58.0	-59.1	-58.0	-59.1	-58.0	0.0	0.0
	-60	-37.3	-38.0	-37.3	-38.0	-37.3	-38.0	0.0	0.0
	0	-95.2	-96.9	-98.1	-97.0	-97.0	-97.0	1.8	0.0
	-20	-77.1	-76.8	-80.3	-77.1	-78.4	-77.0	-1.9	0.1
-0.5	-40	-56.2	-56.4	-58.5	-57.2	-57.3	-56.9	-1.2	0.5
	-60	-35.0	-35.6	-37.5	-37.5	-36.2	-36.8	-1.3	1.3
	0	-91.3	-93.8	-96.6	-93.9	-94.2	-93.9	3.0	0.1
	-20	-72.3	-73.5	-78.7	-74.0	-75.0	-73.8	-3.6	0.3
-1.2	-40	-51.8	-52.6	-56.3	-54.5	-54.2	-53.9	2.4	1.2
	-60	-30.5	-30.9	-36.9	-35.7	-33.3	-33.7	-3.6	2.8

TABLE 6. Variation in THD+N for 1kHz and 997Hz Test Signals Sampled at 48kHz During 6 Simulations Each of 10% Random DAC Code Errors of 0.0, -0.5 and -1.2 LSB Magnitude.

ERROR	LEVEL DB	MAXIMUM 3000	MAXIMUM 3163	MINIMUM 3000	MINIMUM 3163	MEAN 3000	MEAN 3163	MAX DEV 3000	MAX DEV 3163
	0	-99.6	-98.1	-99.6	-98.1	-99.6	-98.1	0.0	0.0
	-20	-82.4	-78.1	-82.4	-78.1	-82.4	-78.1	0.0	0.0
0.0	-40	-59.2	-58.0	-59.2	-58.0	-59.2	-58.0	0.0	0.0
	-60	-38.0	-38.0	-38.0	-38.0	-38.0	-38.0	0.0	0.0
	0	-94.9	-96.9	-101.9	-97.1	-98.9	-97.0	3.9	0.1
	-20	-77.6	-76.8	-83.4	-77.0	-80.2	-77.0	-3.2	0.2
-0.5	-40	-55.4	-56.4	-59.2	-57.1	-57.5	-56.9	2.1	0.5
	-60	-35.4	-35.6	-38.2	-37.5	-37.4	-36.8	2.0	1.3
	0	-90.0	-93.8	-99.6	-94.0	-94.9	-93.9	4.9	-0.2
	-20	-72.5	-73.4	-82.4	-74.0	-75.9	-73.8	-6.5	0.4
-1.2	-40	-51.3	-52.6	-59.2	-54.6	-54.2	-53.8	-5.0	1.2
	-60	-29.9	-30.9	-38.0	-35.7	-35.5	-33.7	5.7	2.8

TABLE 7. Variation in THD+N for 3kHz and 3163Hz Test Signals Sampled at 48kHz During 6 Simulations Each of 10% Random DAC Code Errors of 0.0, -0.5 and -1.2 LSB Magnitude.

ERROR	LEVEL DB	MAXIMUM 315	MAXIMUM 317	MINIMUM 315	MINIMUM 317	MEAN 315	MEAN 317	MAX DEV 315	MAX DEV 317
	0	-99.1	-98.1	-99.1	-98.1	-99.1	-98.1	0.0	0.0
	-20	-78.5	-78.0	-78.5	-78.0	-78.5	-78.0	0.0	0.0
0.0	-40	-57.6	-58.0	-57.6	-58.0	-57.6	-58.0	0.0	0.0
	-60	-37.7	-38.0	-37.7	-38.0	-37.7	-38.0	0.0	0.0
	0	-97.0	-96.9	-98.8	-97.1	-97.8	-97.0	-1.0	-0.1
	-20	-76.9	-76.8	-78.1	-77.0	-77.2	-76.9	-0.9	0.1
-0.5	-40	-56.0	-56.4	-57.3	-57.1	-56.6	-56.9	-0.7	0.5
	-60	-35.1	-35.6	-37.2	-37.5	-36.6	-36.8	1.5	1.2
	0	-92.6	-93.7	-94.6	-94.1	-94.0	-93.9	1.4	0.2
	-20	-73.4	-73.6	-75.2	-73.9	-74.1	-73.8	-1.0	0.2
-1.2	-40	-52.7	-52.6	-56.0	-54.5	-53.7	-53.9	-2.3	1.2
	-60	-30.7	-30.8	-35.5	-35.7	-33.6	-33.6	3.0	2.8

TABLE 8. Variation in THD+N for 315Hz and 317Hz Test Signals Sampled at 44.1kHz During 6 Simulations Each of 10% Random DAC Code Errors of 0.0, -0.5 and -1.2 LSB Magnitude.

ERROR	LEVEL DB	MAXIMUM 1000	MAXIMUM 997	MINIMUM 1000	MINIMUM 997	MEAN 1000	MEAN 997	MAX DEV 1000	MAX DEV 997
	0	-97.8	-98.1	-97.8	-98.1	-97.8	-98.1	0.0	0.0
	-20	-77.9	-78.1	-77.9	-78.1	-77.9	-78.1	0.0	0.0
0.0	-40	-58.0	-58.0	-58.0	-58.0	-58.0	-58.0	0.0	0.0
	-60	-38.0	-38.0	-38.0	-38.0	-38.0	-38.0	0.0	0.0
	0	-96.3	-97.0	-97.0	-97.1	-96.6	-97.0	-0.4	-0.1
	-20	-76.4	-76.8	-76.8	-77.0	-76.6	-76.9	0.2	0.1
-0.5	-40	-56.1	-56.4	-57.3	-57.2	-56.9	-56.9	0.7	0.5
	-60	-35.6	-35.6	-37.6	-37.5	-36.8	-36.8	1.3	1.3
	0	-92.9	-93.8	-94.1	-94.0	-93.5	-93.9	0.6	0.1
	-20	-72.8	-73.5	-73.8	-73.9	-73.2	-73.7	-0.6	0.2
-1.2	-40	-52.2	-52.7	-54.6	-54.5	-53.8	-53.9	1.6	1.2
	-60	-30.8	-30.8	-35.8	-35.7	-33.7	-33.7	2.9	2.8

TABLE 9. Variation in THD+N for 1kHz and 997Hz Test Signals Sampled at 44.1kHz During 6 Simulations Each of 10% Random DAC Code Errors of 0.0, -0.5 and -1.2 LSB Magnitude.

ERROR	LEVEL DB	MAXIMUM 3000	MAXIMUM 3163	MINIMUM 3000	MINIMUM 3163	MEAN 3000	MEAN 3163	MAX DEV 3000	MAX DEV 3163
	0	-97.8	-98.1	-97.8	-98.1	-97.8	-98.1	0.0	0.0
	-20	-77.9	-78.1	-77.9	-78.1	-77.9	-78.1	0.0	0.0
0.0	-40	-58.2	-58.0	-58.2	-58.0	-58.2	-58.0	0.0	0.0
	-60	-38.1	-38.0	-38.1	-38.0	-38.1	-38.0	0.0	0.0
	0	-96.6	-96.9	-97.5	-97.1	-96.8	-97.0	-0.6	0.1
	-20	-75.7	-76.8	-76.8	-77.0	-76.4	-76.9	0.7	0.1
-0.5	-40	-55.9	-56.4	-57.7	-57.2	-56.8	-56.9	0.9	0.5
	-60	-35.6	-35.6	-37.9	-37.5	-37.0	-36.8	1.4	1.3
	0	-93.3	-93.8	-95.1	-94.1	-93.9	-93.9	-1.3	-0.2
	-20	-71.8	-73.5	-73.7	-73.9	-73.2	-73.7	1.4	0.3
-1.2	-40	-51.6	-52.7	-55.0	-54.5	-53.6	-53.8	2.0	1.2
	-60	-30.8	-30.8	-36.4	-35.7	-33.8	-33.6	3.0	2.8

TABLE 10. Variation in THD+N for 3kHz and 3163Hz Test Signals Sampled at 44.1kHz During 6 Simulations Each of 10% Random DAC Code Errors of 0.0, -0.5 and -1.2 LSB Magnitude.

LEVEL (DB)	TOTAL (DB)	FUND. (DB)	THD (DB)	THD (%)	THD+N (DB)	THD+N (%)	CODES
-70	-70.1	-70.1	-36.2	1.5	-28.3	3.8	21
-71	-71.0	-71.1	-37.0	1.4	-27.6	4.2	19
-72	-72.0	-72.1	-35.2	1.7	-26.6	4.7	17
-73	-73.1	-73.1	-32.5	2.4	-25.4	5.4	15
-74	-74.0	-74.0	-28.3	3.8	-23.4	6.8	15
-75	-74.9	-74.9	-28.5	3.8	-23.2	6.9	13
-76	-76.0	-76.0	-28.5	3.8	-22.8	7.2	11
-77	-76.9	-76.9	-24.2	6.2	-20.5	9.4	11
-78	-77.9	-78.0	-25.3	5.4	-20.9	9.0	9
-79	-78.8	-78.8	-21.1	8.8	-18.7	11.6	9
-80	-80.1	-80.2	-20.6	9.3	-18.8	11.5	7
-81	-80.7	-80.8	-19.7	10.4	-17.9	12.7	7
-82	-81.7	-81.9	-16.6	14.8	-15.4	17.0	7
-83	-83.3	-83.4	-17.2	13.8	-15.8	16.2	5
-84	-83.7	-83.8	-17.2	13.8	-15.5	16.8	5
-85	-84.3	-84.4	-15.2	17.4	-14.1	19.7	5
-86	-85.2	-85.6	-12.6	23.4	-11.8	25.7	5
-87	-88.4	-88.7	-11.6	26.3	-11.0	28.2	3
-88	-88.6	-88.9	-11.9	25.4	-11.1	27.9	3
-89	-88.7	-89.1	-11.8	25.7	-11.0	28.2	3
-90	-89.0	-89.4	-11.5	26.6	-10.7	29.2	3
-91	-89.3	-89.7	-10.7	29.2	-10.0	31.6	3
-92	-89.6	-90.3	-9.6	33.1	-9.1	35.1	3
-93	-90.1	-90.9	-8.1	39.4	-7.7	41.2	3
-94	-90.8	-92.0	-6.4	47.9	-6.1	49.5	3
-95	-91.9	-94.0	-4.6	58.9	-4.3	61.0	3
-96	-94.9	-99.7	-2.1	78.5	-1.8	81.3	3

TABLE 11. Theoretical Linearity and Distortion of 1kHz Low Level Test Signals Sampled at 44.1kHz and 16 Bits Precision With a Time Duration of 160ms (7056 samples).

	LEVEL (DB)							
HARMONIC	-95	-90	-85	-80	-75	-70	-65	-60
1	0	0	0	0	0	0	0	0
2	-44	-49	-60	-63	-64	-72	-72	-67
3	-4	-32	-24	-32	-38	-46	-50	-57
4	-45	-49	-49	-60	-50	-62	-58	-67
5	-16	-15	-30	-31	-39	-43	-50	-60
6	-63	-66	-49	-65	-60	-53	-69	-64
7	-16	-16	-25	-32	-39	-44	-48	-62
8	-44	-50	-69	-50	-95	-62	-80	-84
9	-13	-32	-20	-42	-43	-44	-50	-61
10	-46	-48	-59	-48	-82	-98	-78	-63
11	-25	-22	-21	-33	-69	-45	-50	-60
12	-57	-60	-55	-60	-61	-57	-64	-70
13	-20	-21	-49	-32	-39	-50	-51	-65
14	-44	-51	-50	-81	-56	-68	-63	-76
15	-18	-32	-30	-32	-35	-62	-60	-55
16	-46	-48	-50	-61	-58	-77	-55	-65
17	-32	-27	-29	-29	-36	-53	-58	-62
18	-53	-56	-91	-68	-67	-96	-60	-68
19	-22	-24	-28	-25	-57	-49	-60	-62
20	-43	-53	-54	-58	-55	-59	-68	-73
21	-21	-33	-28	-34	-36	-49	-64	-57
TOTAL	-91.9	-89.0	-84.3	-80.1	-74.9	-70.1	-65.0	-60.0
FUND.	-94.0	-89.4	-84.4	-80.2	-74.9	-70.1	-65.0	-60.0
THD	-4.6	-11.5	-15.2	-20.6	-28.5	-36.2	-41.1	-48.6
THD+N	-4.3	-10.7	-14.1	-18.8	-23.2	-28.3	-33.1	-38.0

TABLE 12. Harmonic Spectrum of 1kHz Test Signals Sampled at 44.1kHz and 16 Bits Precision.

ERROR	0.0	-.2	-.5	-1.0	-1.2	-1.5
HARMONIC	DB	DB	DB	DB	DB	DB
1	0	0	0	0	0	0
2	-49	-25	-16	-6	-3	-3
3	-32	-32	-32	-32	-32	-32
4	-49	-31	-21	-12	-8	-2
5	-15	-15	-15	-15	-15	-15
6	-66	-51	-42	-32	-29	-23
7	-16	-16	-16	-16	-16	-16
8	-50	-38	-29	-19	-16	-10
9	-32	-32	-32	-32	-32	-32
10	-48	-38	-29	-19	-16	-10
TOTAL	-89.0	-89.8	-91.0	-92.0	-91.8	-91.0
FUND.	-89.4	-90.3	-91.9	-95.4	-97.3	-101.4
THD	-11.5	-11.3	-10.2	-7.3	-6.3	-5.5
THD+N	-10.7	-10.2	-7.5	-2.7	-1.4	-0.4

TABLE 13. Effect of DAC Nonlinearity on the Spectrum of -90db, 1kHz Test Signals Sampled at 44.1kHz (Error at DAC Code 1).

LEVEL	-95		-90		-80		-70	
ERROR	0.0	-1.2	0.0	-1.2	0.0	-1.2	0.0	-1.2
HARMONIC	DB	DB	DB	DB	DB	DB	DB	DB
1	0	0	0	0	0	0	0	0
2	-44	2	-49	-3	-63	-24	-72	-43
3	-4	-4	-32	-32	-32	-29	-46	-50
4	-45	-4	-49	-8	-60	-33	-62	-43
5	-16	-16	-15	-15	-31	-20	-43	-40
6	-63	-26	-66	-29	-65	-34	-53	-44
7	-16	-16	-16	-16	-32	-32	-44	-55
8	-44	-9	-50	-16	-50	-27	-62	-46
9	-13	-13	-32	-32	-42	-32	-44	-39
10	-46	-13	-48	-16	-48	-26	-98	-48
TOTAL	-91.9	-94.8	-89.0	-91.8	-80.1	-80.2	-70.1	-70.1
FUND.	-94.0	-101.9	-89.4	-97.3	-80.2	-80.4	-70.1	-70.1
THD	-4.6	-2.7	-11.5	-6.3	-20.6	-15.1	-36.2	-31.5
THD+N	-4.3	-0.9	-10.7	-1.4	-18.8	-13.9	-28.3	-26.3

TABLE 14. Effect of DAC Nonlinearity on the Spectrum of 1kHz Test Signals Sampled at 44.1kHz (Error at DAC Code 1).

LEVEL	-70		-60	
ERROR	0.0	-1.2	0.0	-1.2
HARMONIC	DB	DB	DB	DB
1	0	0	0	0
2	-72	-31	-67	-63
3	-46	-31	-57	-55
4	-63	-34	-67	-66
5	-43	-34	-60	-70
6	-53	-42	-65	-64
7	-44	-41	-62	-57
8	-62	-55	-84	-66
9	-44	-54	-61	-63
10	-98	-44	-63	-60
TOTAL	-70.1	-70.3	-60.0	-60.0
FUND.	-70.1	-70.3	-60.0	-60.0
THD	-36.2	-25.7	-48.6	-47.8
THD+N	-28.3	-23.5	-38.0	-37.4

TABLE 15. Effect of DAC Nonlinearity on the Spectrum of 1kHz Test Signals Sampled at 44.1kHz (Error at DAC Code 10).

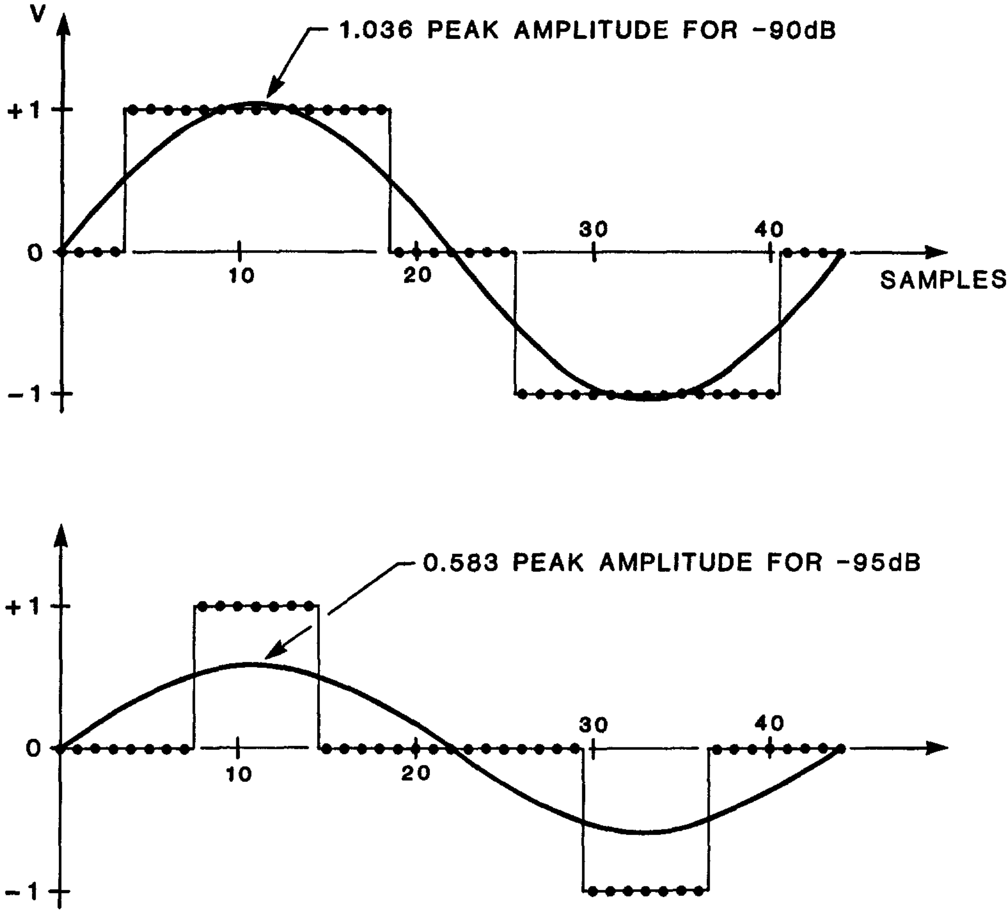


FIGURE 1. Typical Quantized Waveform Sections of -90dB and -95dB, 1kHz Signals Sampled at 44.1kHz and 16 Bits Precision.

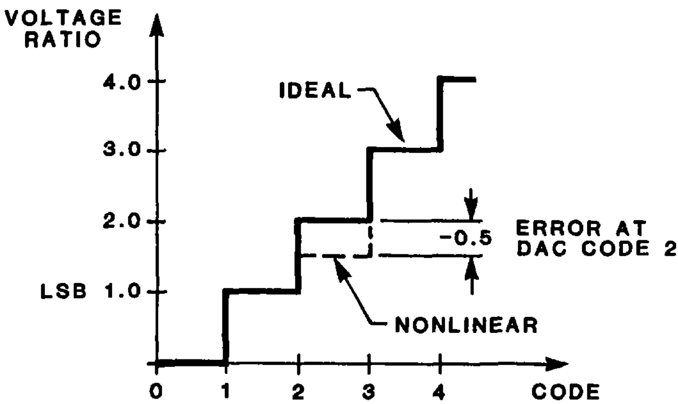


FIGURE 2. Ideal and Nonlinear DAC Transfer Characteristic.

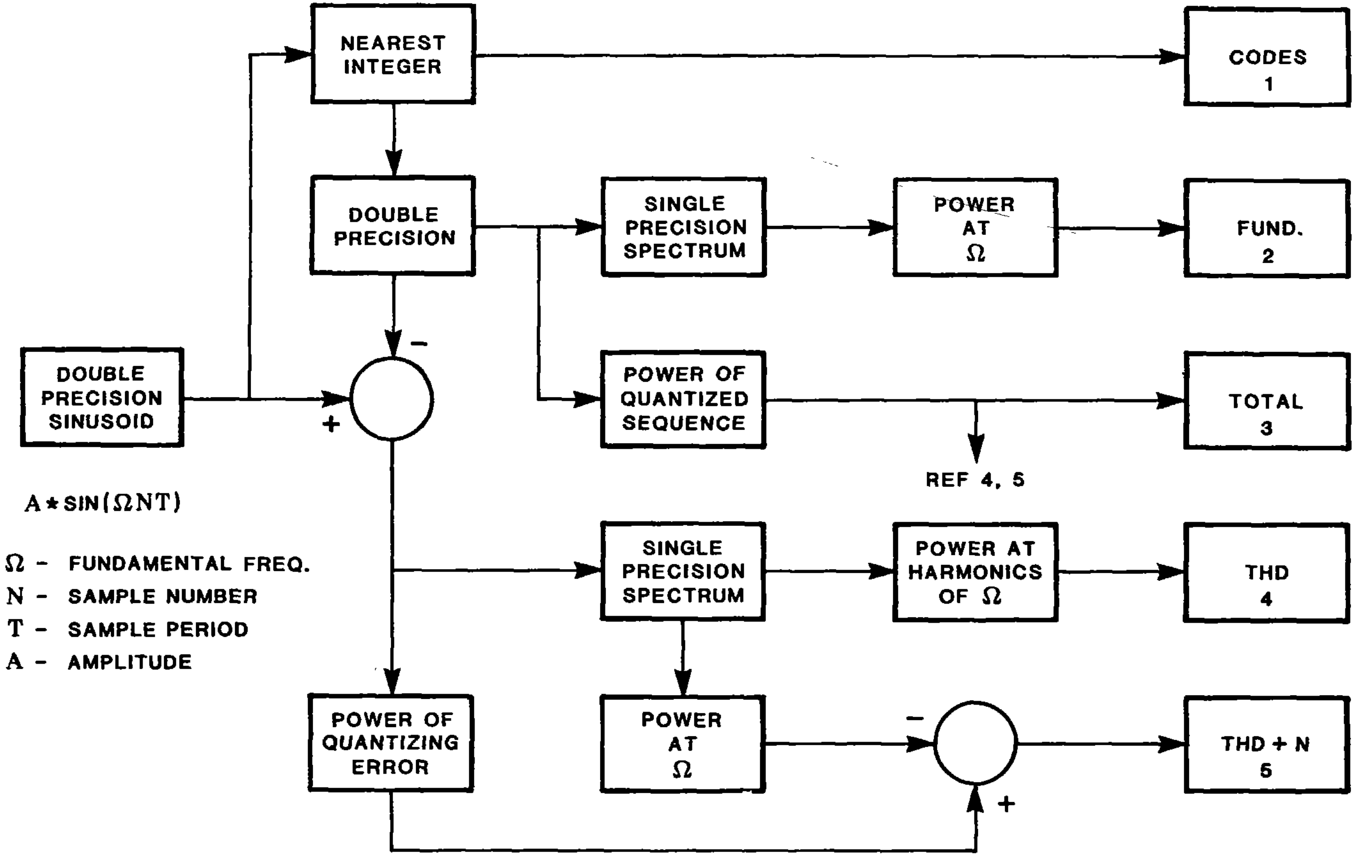
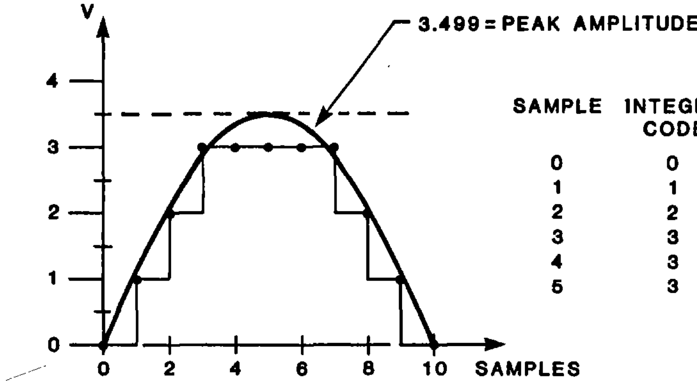


FIGURE 3. Block Diagram of Analysis Procedure.



SAMPLE	INTEGER CODE	BINARY (msb - lsb)
0	0	(0 0 0)
1	1	(0 0 1)
2	2	(0 1 0)
3	3	(0 1 1)
4	3	(0 1 1)
5	3	(0 1 1)

FIGURE 4. Illustration of Basic Encoding Process Used to Determine Number of Codes of a Test Signal Sequence.