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AN AUDIO ENGINEERING SOCIETY PREPRINT

A NEW CLASS OF IN-BAND MULTITONE TEST SIGNALS

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An in-band multitone test signal designed to maximize detection of harmonic, intermodulation, aharmonic and cross-modulation products, despite the presence of multiple frequencies in the test signal, is presented. Measurements of electroacoustic systems are presented and contrasted against traditional harmonic distortion and intermodulation measurements. Measurements of other audio components, such as electronics, is also explored.

0 Introduction

One of the stimuli for this project was a search for a test signal to better correlate with perceived listening clarity. Examination of a device using only harmonic distortion measurements does not provide a straightforward and consistent relationship between the measurements and listening results, especially once the measured harmonic distortion falls below a certain level. Traditionally used intermodulation test signals were considered, but these typically tend to provide only a few intermodulation or crossmodulation products within the audio band. Multitone signals looked to be the most promising type of measurement, as these would provide a complex stimulus for the DUT, and generate a larger number of intermodulation and crossmodulation products.

1.0 Limitations of Existing Signals

1.1 Harmonic Distortion

It can be confusing to try and correlate harmonic distortion measurements with what is heard. Once harmonic distortion levels are below several percent in the midband, it is a tossup as to which device will sound better or clearer. Up to a certain point, a given level of even order harmonics are more benign sonically than a given level of odd order harmonics, while higher orders are generally more irritating than the lower order harmonics. A significant amount of second harmonic distortion may actually sound preferable to much lower amounts of third or fifth harmonics. A certain amount of second harmonic distortion may even be preferred to a system that has little or no second harmonic distortion. With all these confusing factors, harmonic distortion is not a clear cut way to evaluate a system or device once the levels have reached typical values for a modern high performance audio device.

1.2 Intermodulation Distortion

Intermodulation distortion measurements typically use just two tones, such as SMPTE, DIN, or CCIF, with a limited number of intermodulation and crossmodulation products within the audio band. There are a few three tone intermodulation tests that were proposed, but they have not become popular or mainstream tests. (1) The classic two-tone tests are severely limited in how much distortion across the audio band they will expose. Even performing multiple tests using all the variations of the mainstream

intermodulation tests will still leave large gaps in the characterization of the DUT's intermodulation distortion performance, and consume a fair amount of time.

1.3 Spectral Contamination

Spectral Contamination testing has been proposed by Sokolich and Jensen (2). This looks more promising, but one of the proposed test signals covered in the paper is completely outside of the audio band, with signal stimulus extending from 150 kHz to 300 kHz, and it uses equal frequency spacing; in the example used in the paper, 9.36 kHz. The other proposed test signal spectrum extends from 10 kHz to 25 kHz, and has 120 Hz signal spacing. Equal frequency spacing means that many of the various intermodulation products and even some of the crossmodulation products will have the same resultant frequency. In the out of band version, this does generate a range of signals spaced 9.36 kHz apart in the audio band. For the 10 kHz to 25 kHz stimulus with 120 Hz spacing, the audio band distortion products tend to be at 120 Hz spacing, with a lot of the products at 120 Hz.

Placing the stimulus frequencies all outside of the audio band means that the device or system under test must possess greatly extended bandwidth and a concurrent extension of linearity, which may or may not relate to use within the audio band. It also means that the signal is ineffective for use with inherently bandwidth-limited systems such as loudspeakers, and most current digital audio systems. Additionally, the distortion products must all be of two kinds: crossmodulation products that divide down into the audio band and intermodulation products that subtract down into the audio band. No harmonics will be present within the audio band.

The version with the stimulus band from 10 kHz to 25 kHz still limits the use to wide band electronics, and precludes most digital and acoustic systems from being measured with this signal. It has similar restrictions as to what distortion products are displayed.

A third test signal is suggested, one which has signal components within the audio band, and a space or gap left in the middle of the band. This is designated as an "in-band" measurement. No frequencies or other details are suggested, and no measurements were performed using this signal in the Sokolich and Jensen paper.

1.4 SYSid Version of Spectral Contamination

Spectral contamination as performed by the SYSid measurement system has an in-band form of spectral contamination measurement. This signal has already found some use in correlating perceived clarity with the measurement (3). However, the usefulness is not as complete as it could be. In the default setup file, the frequencies either have equal spacing, or arbitrary spacing between the multiple frequencies. A total of 15 tones are used, with default frequencies of: 80, 100, 120, 160, 200, 240, 300, 400, 500, 700, 900, 1200, 1500, 2000 and 3000 Hz, which is spacing of: 20, 40, 60, 100, 200,

300, 500, 1000 Hz, this yields frequency to next frequency ratio's (or multiplier's) of 1.2, 1.25, 1.33, 1.4 and 1.5, not necessarily in any given order.

A formula is given in the owner's manual to achieve equal log spacing within a specified band, but this results in tone spacing that are a product of a given chosen bandwidth and number of tones, and has no other purpose other than to provide the equal spacing. The results from this formula are virtually random with respect to frequency spacing ratio's. A utility is provided called GENFN, which allows custom selection of the test frequencies for the SYSid spectral contamination test. The test frequencies selected and entered are placed into the closest FFT bin. This is done to maximize the ability of the FFT to examine the frequencies between these filled bins, but may make the spacing turn out to be less than optimum.

There is an admonition in the owner's manual to avoid making the test frequencies an integer multiple of one another, but this does not prevent the frequency spacing from generating intermodulation or crossmodulation products that can be covered up by a primary tone. For instance, intermodulation products that fall at 100 Hz or 200 Hz are completely masked by the primary tones at these frequencies. These frequency spacing allow the harmonics of the lower frequency test signals to be covered up as well, so even simple harmonic distortion products are hidden for some of the test signal tones.

The sheer number of tones can also present a problem in some cases, as the level of individual tones within the multitone signal must be at least 23.53 dB down from nominal in order to avoid clipping and other gross errors due to phase shifts in the system under test. This effectively limits the available measurement dynamic range with a 16 bit testing system to about 72 dB or less. The author is not aware of any capability within SYSid to set the relative phase of the various test tones.

Also, the number of tones within that frequency range makes it difficult to ascertain exactly where the distortion products are coming from, due to limitations in spectrum analyzer resolution. The density of the primary tones makes it hard to clearly ascertain the origin of the distortion products that are not already covered up by primary tones. This forces the use of the highest spectral resolution that the system is capable of, and still limits how accurately some of the distortion products can be ascertained.

Another concern with the SYSid default setup frequencies is that lower order harmonics are only present up to a certain point. The last primary frequency in the test signal is 3 kHz, and stopping the test signal content at this frequency limits the ability to determine both the level of harmonics for the rest of the audio band above 3 kHz, and the ability to detect intermodulation and crossmodulation products at higher frequencies. The limited band that the signal covers essentially limits its use to the upper bass and midrange. Two or three way speaker systems would have virtually no excitation of the tweeter with this test signal.

The sequence starts out fairly low at 80 Hz, or even lower if a default file with a start frequency of 60 Hz is used, which is beyond the full capability of some smaller speaker systems and some other bandlimited systems. In my opinion, a widely acceptable test signal should be useful on almost any audio device, even a bandlimited one. A low frequency of 100 Hz is more appropriate for a test signal to have a more universal application.

To the credit of the designers, the flexibility of the SYSid test system allows the user to generate a user defined set of spectral contamination test tones. This will enable the SYSid system to take advantage of the newly designed test signals presented herein.

1.5 Audio Precision Multitone Signals

The Audio Precision System One DSP and System Two both have a multitone in-band test signal capability, with the default setup having frequencies spaced according to 1/3 octave ISO centers, which is a multiplier ratio of 1.25. With this spacing, every third frequency is spaced an octave apart, and the resultant frequencies often end up at even spacing amounts. A total of 31 separate tones are used, which reduces the dynamic range available. Individual tones must be at -29.83 dB from nominal, unless phase manipulation is used to reduce the crest factor. As noted earlier, this may not be a good idea if the system or device under test is known to have amplitude roll-off in the audio band, excess phase shifts or time delays built into the system.

Audio Precision does adjust the frequencies to correspond to an FFT analyzer bin center frequency, in order to maximize the ability to use the empty analyzer bins to best advantage. These 31 frequencies are: 16.15, 21.53, 26.92, 43.07, 53.83, 64.60, 80.75, 102.28, 123.82, 156.12, 199.18, 253.02, 317.61, 398.36, 500.65, 635.23, 802.11, 1001.3, 1248.9, 1598.8, 1997.2, 2503.2, 3154.6, 3999.8, 4995.7, 6352.3, 7999.6, 10002, 12500, 16005, and 19999 Hz. Note that none deviate from the standard ISO centers by more than about 5 Hz.

This does offset the exact regularity that would tend to occur with such ISO-center frequency spacing, but since the analyzer bins are limiting the ability to resolve the distortion products to any better accuracy, these minor offsets are not very effective in avoiding intermodulation and crossmodulation product cover up, or harmonic cover up by the primary tones. Even with the slight offset in the stacking up of harmonics, intermodulation and crossmodulation products will not be able to be resolved due to the inherent width of the FFT bins.

The Audio Precision systems can be programmed or set to generate and test using any frequencies chosen by the user, but they do not offer a means or advice on avoiding the generation of multiple distortion products at the same resultant frequency, and at the same frequencies as some of the primary tones.

There is an AP codec test signal (5), which has two bands of 8 frequencies (16 total) separated by a two octave gap. These are not all at ISO centers, +/- the FFT bin

center, but they still exhibit some stacking of distortion products. This test signal is similar to the one proposed by Sokolich and Jensen.

The frequencies are: 53.83, 123.82, 209.95, 312.23, 446.81, 608.31, 807.50, 1060.5, 3999.8, 5022.6, 6287.7, 7859.6, 9808.4, 12230, 15234, and 18965 Hz.

The frequency spacing for the various tones is not according to any pattern or design that is readily apparent. Information about this particular AP test signal was not received until the basic research for this paper had been completed.

2.0 New Spectral Contamination Signal

After discovering that harmonic, intermodulation, and crossmodulation products were being masked to one extent or another by the present implementations of spectral contamination tests, I sought a series of frequencies which would avoid this problem. A number of options were explored, and while frequencies could be picked at random, or arbitrarily, it was felt that some sort of defining function or multiplier would be more useful and consistent. It was found that a multiplier based on the Golden Ratio, or the final ratio of the mathematical Fibonacci sequence, of 0.618034 worked very well. By using a multiplier of 1.618 or 2.618, a sequence of tones is generated that avoids any of the harmonics, and prevents almost all of the intermodulation and cross-modulation products from being covered up spectrally by any of the other tones or products.

2.1 Working Criteria

It was desired that the tone sequence start and stay within the audio band, so that bandlimited systems would be fully excited by the test stimulus. Accordingly, 100 Hz was arbitrarily chosen as a start frequency that was well within the range of even small multimedia loudspeakers. This results in a series of 6 tones using the 2.618 multiplier at frequencies of: 100, 261.8, 685.4, 1794.4, 4697.9, and 12299 Hz for the test signal I call the Phi6 spectral signal. Figure 1 graphically depicts the FFT spectrum of the signal as output from a CD player, through a mixer for level control.

In an effort to limit the loss of dynamic range, it was decided that there should be a practical limit to how many tones were used. Starting from 100 Hz, and using the 1.618 multiplier, 12 tones within the audio band result, and this was felt to be a good upper limit. Using a much lower frequency only results in a few more tones within the audio band, and these frequencies are all fairly low.

The 12 tone signal using the 1.618 multiplier results in the former frequencies plus: 161.8 Hz, 423.6 Hz, 1109.0 Hz, 2903.4 Hz, 7601.3 Hz, 19900 Hz, and is called a Phi12 spectral signal. Figure 2 graphically depicts the FFT spectrum of the signal from the CD player, and through the mixer.

Further refinements and variations on the test signals suggested themselves after working with the proposed test signals to actually measure a system. These variations are covered in the experimental results section, as they were developed as a result of the experimentation.

3.0 Experimental Results

Experimental multitone test signals were generated using a PC based waveform generator operating in the digital domain, and transferring the final product to CD-R for playback and use.

It was found that some CD players were unable to handle output to full 0 dBFS, with the result a much higher level of distortion. It was as if some component was either clipping or compressing the signal, generating harmonics, intermodulation and crossmodulation products all throughout the spectrum. Accordingly, it was found that reducing the level of the digitally generated recorded signal by 2 dB was enough for most players to avoid this problem. In order to avoid any vestige of amplitude related compression or clipping, the signals were generated and recorded with peak signal levels below -3 dB. Some players still had a problem with these peak levels, but most did not. The author suspects the digital filtering within the CD player may be the cause.

3.1 Revisions

The original Phi12 stimulus had some distortion product cover up, due to some of the intermediate tones intermodulating with each other, and generating the same frequency. Once this was discovered, a revised version that used different multipliers for each of the 6 base tones was devised. While this did include some arbitrary multiplier choices, and could conceivably be improved, it was found useful as a more complex stimulus than the 6 tone version.

Accordingly, from the base frequency of 100 Hz, a multiplier of 1.22 was used, resulting in 122 Hz. From 261.8 Hz, a multiplier of 1.33 was used, resulting in 348.2 Hz, from 685.4 Hz, a multiplier of 1.44 resulting 987.0 Hz, from 1794 Hz a multiplier of 1.6 resulting in 2870.4 Hz, from 4697.9 Hz, a multiplier of 1.44 resulting in 6765.0 Hz, from 12299 Hz, a multiplier of 1.33, resulting in 16358 Hz. None of these has obvious intermodulation or crossmodulation products that occur at exactly the same frequency. Most distortion products are far enough apart for a spectrum analyzer to differentiate between the different products. Figure 3 is the FFT spectrum of this signal, from a CD player through a mixer.

4.0 Further Test Signal Refinements

Other changes and refinements were considered to reduce or alleviate some of the limitations of the signal.

4.1 Possible Crest Factor Reduction

Proper phasing of the various signal tones can provide some relief, but a DUT that had significant amplitude changes, roll-off or phase shifts would destroy the carefully orchestrated phase relationships of the original test signal. It is recommended that full allowance be made for the worst case crest factor of the multiple tones. Several references regarding such phase manipulation are provided. (4)

4.2 Split Octave Bands - High Low

After working experimentally with some of the variations on the signals, it was determined that more tones or a higher density of tone spacing might be desirable to highlight intermodulation and cross-modulation distortions, and provide more distortion products across the audio band. It was also determined that limiting the total number of individual tones would help preserve dynamic range.

To raise the tone interval density without increasing the number of tones to a high number, isolated octave bands of tones was considered. A suitably non-overlapping multiplier was desired, so a multiplier of one plus one tenth the original full audio band multipliers were investigated. Scatter diagrams were used to evaluate the suitability of various octave band combinations with a reasonable total number of tones, that would provide a wide range of harmonic, intermodulation, and crossmodulation products. One of the concerns was to limit the spread of each group or band of signals to an octave or less, so that the second harmonics of the band would not be covered up by the primary tones.

A pair of split octave bands was found to provide an efficient and useful multitone test signal without an excessive number of individual tones. An octave starting at 100 Hz, in conjunction with an octave starting at 5 kHz, with both containing five tones, and with spacing multipliers of 1.1618. This results in frequencies of 100, 116.18, 134.98, 156.80 and 182.19 Hz for the low band, and of 5000, 5809, 6748.9, 7840.9, and 9109.6 Hz. This test signal proved particularly efficacious at ferreting out intermodulation and crossmodulation in two-way loudspeakers. Figure 4 depicts the FFT spectrum of this signal, from a CD player through a mixer.

Note that this is similar in spirit to the third signal proposed by Sokolich and Jensen, but not identical. Much larger areas are left open for distortion products to manifest and be readily observed.

Other split band combinations were investigated, such as:

100 -182 Hz plus 10 - 18.2 kHz, with frequencies of 100, 116.18, 134.98, 156.80 and 182.19 Hz for the low band, and 10000, 11618, 13498, 15682, and 18219 Hz for the high band. Figure 5.

100 - 182 Hz plus 1.11 - 2.02 kHz, with frequencies of 100, 116.18, 134.98, 156.80 and 182.19 Hz for the low band, and 1109.0, 1288.4, 1496.9, 1739.1, 2020.5 Hz for the high band. Figure 6.

261 - 477 Hz plus 1.11 - 2.02 kHz, with frequencies of 261.80, 304.16, 353.38, 410.56, and 476.99 Hz for the low band, and 1109.0, 1288.4, 1496.9, 1739.1, 2020.5 Hz for the high band. Figure 7.

261 - 477 Hz plus 10 - 18.2 kHz, with frequencies of 261.80, 304.16, 353.38, 410.56, and 476.99 Hz for the low band, and 10000, 11618, 13498, 15682, and 18219 Hz for the high band. Figure 8.

685 - 1249 Hz plus 1.79 - 3.27 kHz, with frequencies of 685.41, 796.31, 925.16, 1074.9, and 1248.8 Hz for the low band, and 1794.4, 2084.8, 2422.1, 2814.0, and 3269.3 Hz for the high band. Figure 9.

4.3 Revised Split Octave Band Signal

It proves all too easy to fall into the same trap as before. In selecting even starting frequencies, such as 100 Hz for the low band, and 10 kHz for the high band, some of the harmonics, intermodulation and crossmodulation products line up again, covering up the source of the tones responsible for the distortion.

After trying a different start frequency that was not an even multiple of the other start frequency for the high band or the low band, it was realized that by using the same multiplier for each band, the top band of frequencies would divide into the bottom band and have the same crossmodulation product. This leads to the need for a different multiplier for the separate bands. After checking for this, a slightly different multiplier for one of the bands was used, 1.2618 vs. 1.1618.

Use of the new 1.2618 multiplier results in the high frequency band extending for a bit more than an octave, but the author considers this to be completely arbitrary and a minor issue. If a band of closely spaced multitone frequencies extends past an octave, some potential exists for cover-up of harmonics. For the higher frequency bands where this was done, the resolution is sufficient to allow determination of the 2nd harmonics without difficulty. This is why the low frequency band uses the originally derived multiplier.

At this point, a spread sheet was developed for use in evaluating the resultant distortion products that would occur with various primary test signal tones in a spectral type test signal.

Figure 10 is a copy of the spread sheet for the Phi6 spectral signal, Figure 11 is a scatter diagram of the primary tones for the Phi6 spectral, harmonics (up to the tenth), and intermodulation and crossmodulation products. Figure 12 is the spread sheet for the Phi12 spectral signal, and Figure 13 the scatter diagram. Figure 14 is the spread

sheet for the Phi12r (revised), and Figure 15 the scatter diagram. Figure 16 is the spread sheet for the first split band spectral, the one with bands at 100 -182 Hz plus 5 - 9.1 kHz.

Experimental results for the first set of split band spectral test signals reveal that the pairings with the low band at 261 to 477 Hz did not show any additional distortion products than the ones with the low band from 100 to 182 Hz. They also do not show low frequency second harmonics as readily. Also, the pairings that had the high band in the last octave do not show any high frequency second harmonics, or intermodulation or crossmodulation products on the high side before the audio band was exceeded. In order to address this, revised split band signals were reduced to a set of low and high band signals, and a set of low and middle band signals.

The revised split band spectral's now use frequencies at: 100 -182 Hz plus 4.7 - 11.9 kHz, with frequencies of 100, 116.18, 134.98, 156.80 and 182.19 Hz for the low band, and 4697.9, 5927.8, 7479.7, 9437.9 and 11909 Hz for the high band for the low/high band pairing, and called a Phi Low-High split band spectral. Shown in Figure 17.

The low/middle revised split band now uses frequencies at: 100, 116.18, 134.98, 156.80 and 182.19 Hz for the low band, and 986.99, 1245.4, 1571.4, 1982.8 and 2502.0 Hz, and I call it a Phi Low-Middle split band spectral. Figure 18.

4.4 Phi Tri-Band Spectral Signal

Further work with these split band spectral signals resulted in the development of a split band signal with components at low, middle AND higher frequencies, which left two large open areas for distortion products to show up. The multipliers have to be different for each band. The total number of tones needs to be kept down, so three clusters of four frequencies was used, for a total of 12 separate tones. Multipliers of 1.1618, 1.2618 and 1.12618 were used for the three bands respectively. The frequencies that result are: 100, 116.18, 134.98, and 156.80 Hz for the low frequency band, 986.99, 1245.4, 1571.4, and 1982.8 Hz for the middle band, and 6764.9, 7618.5, 8579.8 and 9662.5 Hz for the high frequency band. I refer to this one as a Phi tri-band spectral, shown in Figure 19.

The frequency ranges were chosen based on earlier work with split band multitone's, and what the author felt would be good ranges for excitation frequencies. Each band has an empty space of approximately two octaves in-between, the low band two octaves below, and the high band an octave above (within the audio band). The start frequency of each band is based on the revised Phi12 (Phi12r) spectral contamination test signal. The underlying premise is that none of the frequencies within each band, including the start frequency, would encourage distortion products to be covered up by other products, or by the primary tones.

5.0 Actual Measurement Results

Unless otherwise noted, the electrical tests all had their level adjusted with a mixer to bring the signal up to the same approximate input level to the FFT spectrum analyzer, so as to maximize dynamic range and the display of potential distortion products. The mixer and complete signal playback system used as the source for the tests were checked to assure that the distortion components arising from these components did not add to, or limit the measured performance of any of the tests.

5.1 Electrical, Record/Playback Devices Measured

Several CD players were checked with the new signals, the professional balanced output player used as the signal source worked well, and a top of the line consumer CD player had an even lower noise and distortion floor, see Figure 20. A portable CD player with a line out showed good results too, see Figure 21, the gray spectrum.

Headphone output jacks on portables were another story, as depicted in the black graph of Figure 21. This is the same player, the lower curve out of the line level jack, and the curve showing a higher level of distortion and noise being from the headphone out jack.

Several CD players measured had problems when the recorded signal had peaks at digital 0 dBFS, where they exhibited symptoms of clipping/compression. Figure 22 shows this effect to a moderate degree. Figure 23 depicts the difference between 0 dBFS recorded levels, and -6 dBFS recorded levels on another portable player. It can be seen that a reduction of recorded level by 6 dB has reduced distortion by over 20 dB. Gain has been added via a mixer to keep the input levels to the FFT analyzer the same, the only difference is the level recorded on the CD.

A high quality consumer cassette deck was examined via a record/playback of the test signal, using Dolby B noise reduction. The source was the high quality CD player shown in Figure 20. Figures 24, 25, 26 and 27 show the response of the cassette deck when the test signals were recorded at 0 VU levels, accounting for pre-emphasis. Note the presence of distortion and modulation components at fairly high levels. The high frequency content of the test signals in Figures 24, 25 and 27 prevents the normal advantage the Dolby B high frequency noise reduction provides.

A consumer Mini Disc deck was tested, and the results depicted in Figures 28, 29, 30 and 31. In Figure 28, the Phi12r spectral signal, the noise and distortion in-between the signals reaches levels as high as with the cassette deck. Note the generally lower levels of distortion products and noise with the split band signals in between the signal bands compared to the cassette deck. One of the original split band spectral test signals did show a high frequency roll-off with the band containing frequencies at 100 - 182 Hz plus 10 - 18.2 kHz. The last tone in the high frequency band was noticeably attenuated, in contrast to the high quality consumer cassette deck. See Figure 32.

A digitally based crossover and filter system was tested using the Phi12r spectral test signal, shown in Figure 33. The test signal passed through the A to D and the D to A stages without any digital filtering or EQ operations being performed on the signal. Note the rise in the noise floor of over 10 dB, and a few very low level products, compared to the source CD player. Interestingly enough, once a filtering algorithm was engaged, the noise floor went down some, as seen in Figure 34, yet it is still higher than the source.

As can be seen from the test measurements, the new signal is effective in testing electronics, digital systems, and recording systems. I have no doubt that it would be useful for the testing of various transmission systems as well, especially transmission systems using companding. However, access to such systems was limited, and the author was unable to present measurement results within this paper.

5.2 Electroacoustic Loudspeaker Tests

The new test signal proved highly effective in measuring loudspeakers, as they tend to have a much higher level of intermodulation and crossmodulation than electronics and similar systems. Changes in the distortion content with changes in drive level were easily noted. All loudspeaker measurements were taken in an anechoic chamber, at 1M, unless otherwise noted.

Figure 35 shows the distortion for a commercial plastic injection molded 15" based two-way system with a 1" throat compression driver (called Speaker A), at one watt RMS drive levels for the Phi6 test signal. Note the distortion products clearly visible in the middle/high range. Figure 36 is this same speaker at 10 watts RMS drive level, and the distortion has risen considerably. Figure 37 depicts this same system with the Phi12r test signal. The higher density of potential distortion products allows a clearer picture of where the speaker is running into trouble. Contrast this with the overlay of the same loudspeaker tested with all the different original split band spectral signals that were explored (Figures 4 through 9) , in Figure 38. An obvious problem can be seen centered around 1 kHz, and again at 4 kHz. With only one measurement, the Phi12r reveals substantially the same clues of trouble. The tri-band spectral also provides a similar level of information with one measurement.

Conventional harmonic distortion plots do not provide much of an indication that this speaker has a problem. See Figure 39. The levels of harmonic distortion are not unusually high, and do not predict that this speaker will sound fuzzy or less clear than another. Further spectral signal test measurements at 10 watts are shown in Figures 40, 41, and 42.

To provide a reference point, a prototype plastic injection molded 15" based two way with a 1" compression driver (Speaker B) is compared. In Figure 43, it can be seen that speaker B has 10, and up to 15 dB less distortion than speaker A. The harmonic distortion plots for speaker B are not radically different than those for speaker A, yet the

intermodulation and crossmodulation is substantially lower. Figures 44, 45, and 46 show the comparison with the split band spectral signals.

A 2-way nearfield studio monitor prototype using a 6 1/2" woofer, and a 1" titanium dome tweeter is tested at 1W RMS in Figures 47, 48, and 49. The speakers are measured at 1/2M to increase the signal to noise ratio, and attempt to show the very low spectral contamination of the unit. The input level is consistent with intended usage, and it should be noted that a 1W RMS signal level has peaks of close to 100W with these multitone spectral signals! This is excellent performance for a loudspeaker system by any standard, and provides an interesting contrast with the sound reinforcement speakers measured above (Speakers A and B).

Individual drivers can be tested using these signals. An inexpensive stamped frame woofer is tested in Figures 50 and 51. The test signal is input to the woofer full range. Measurements of a compression driver tweeter in Figures 52 and 53 are filtered at 1 kHz at a 12 dB/octave rate to protect the driver, but the low frequency components of the signal still have their effect on the total distortion, and increase the presence of low frequency intermodulation products.

5.3 Electrical Current Tests on Bi-Wired Speaker Cables

One of the other original motivations for investigating this type of test signal was the desire to be able to objectively explore the performance of the various forms of audio cables: line level interconnects, speaker cables, microphone cables, etc. In that respect, it is a bit of a disappointment, but one interesting measurement result did develop. For many years, a debate has raged regarding any possible benefit of using two separate cables to wire a speaker with electrically separated crossover sections, or bi-wiring as it is known.

Theory indicates that if any advantage is to be had, it would have to manifest as a reduction in intermodulation between the low frequency currents and the high frequency currents in the cable. Separating the two ranges should provide a measurable benefit. The signals developed and refined in this paper are highly sensitive to intermodulation and crossmodulation distortion products, so what better test signal than a multitone spectral?

A wide-band current transformer loop was used to measure the current flowing through the speaker cable/s. First the single speaker wire was measured, Figure 55. These are distortion products of the electrical current signal through the cable, and can be seen to be about 45 to 55 dB down from the primary tone's level's. Then the current transformer was placed on the tweeter cable of a bi-wiring arrangement, Figure 56. Note the reduction of low frequency currents in the first spectral tone band, and the reduction of distortion products by 20 dB or more through the entire midrange. Figure 57 depicts the current flowing through the woofer side of the bi-wire cables. Some reduction in distortion products is present in the high frequency regions, starting as low as 1.5 kHz, and reaching reductions of 10 dB. Figure 58 is the full range single cable

overlaid with the tweeter bi-wire cable, and the reduction in distortion products is readily discernible.

Tests on different single speaker cables have so far been inconclusive, with inconsistent differences of only 2-4 dB at the limits of the test system resolution, which are not definitive enough to be able to draw any conclusions. Interesting measurement and data, nonetheless.

6.0 Conclusion

An improved method of selecting frequencies for a multitone test signal has been presented, one which allows the distortion products from the test signal to avoid being covered up by the primary signal tones or other distortion products. Measurements taken using the improved method have indicated that it is a highly effective test signal, and shows promise for use in testing not only electroacoustic systems, but audio electronic, recording and transmission systems. Standardization and selection of such a multitone signal could prove useful to all audio engineers for use with virtually all aspects of audio system and component testing, and may lead to a better correlation of objective measurements with subjective listening test results.

7.0 Acknowledgements

I would like to thank Bill Whitlock of Jensen Transformers for originally sending me the information about the spectral contamination test signal developed by Sokolich and Jensen. I thank Charles Hughes for his help with this manuscript and for discussing some of the concepts and ideas with me, especially the split band spectral signals, and Peavey Electronics Corporation for encouraging me to present this paper. Thanks also to my wife Patricia, without whose patience and understanding I could never have finished this.

8.0 References

- (1) Robert R. Cordell, "A Fully In-Band Multitone Test for Transient Intermodulation Distortion", JAES Vol. 29 Issue 7/8.
- (2) Deane Jensen and Gary Sokolich, "Spectral Contamination Measurement", AES Preprint #2725
- (3) Mix magazine, May 1998, p. 142, review of the Benson StudioStat 8.2, Lab analysis, by Mike Klasco and June 1998, p. 174, review of the KRK Systems Expose Series E-8, Lab Analysis by Jack Hidley.
- (4) Stephen Boyd, "Multitone Signals with Low Crest Factor", IEEE Trans. on Circuits and Systems, Vol. 33, #19, Oct. 1986
Mathias Friese, "Multitone Signals with Low Crest Factor", IEEE Trans. on Communications, Vol. 43, #10, Oct. 1997

Larry J. Greenstein & Patrick J. Fitzgerald, "Phasing Multitone Signals to Minimize Peak Factors", IEEE Trans. on Communications, Vol. 29, #7, July 1981

(5) Richard C. Cabot, "Performance Assessment of Reduced Bit Rate Codecs", presented at the AES Conference "Managing the Bit Budget", London, May 1994. Available as a reprint from Audio Precision upon request.

Appendix A - Equipment used in analysis of spectral test signals

CD player, primary signal source from digitally generated CD-R's: Marantz PMD 321
Mixer: Peavey RSM 1662
Microphone: ACO 7012
Mic Preamp/Meter: Larson Davis Model 800B
FFT Analysis, HD plots, Frequency Response Plots: TEF 20, SLX software, FFT 8192 point mode
Power Amplifier: Peavey CS-1200
Wide-band Current Transformer: Pearson Electronics Model 411

Appendix B

Late in the finalization of this preprint, the author was made aware that Tektronix had at one time a test and measurement unit that can generate multitone signals. The unit is the Tektronix AM700. No details are known at this time about what frequencies are used, or any other details, such as if the unit has programable frequency selection. This model may be discontinued, so contact Tektronix for the most recent and up to date information.

Phi6 Spectral

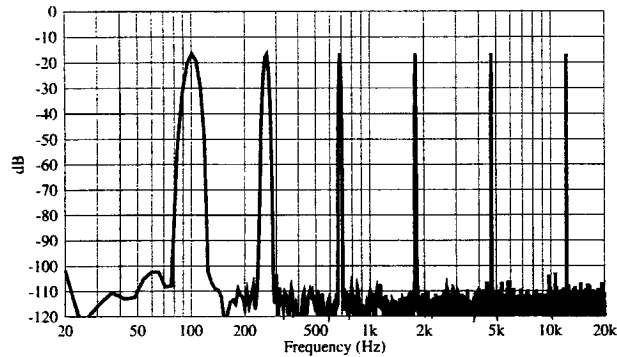


Figure 1

— Lab CD Player Output

Phi12 Spectral, Original

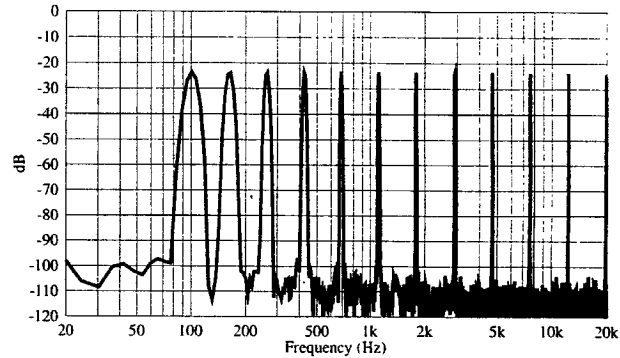


Figure 2

— Lab CD Player Output

Phi12 Spectral, Revised

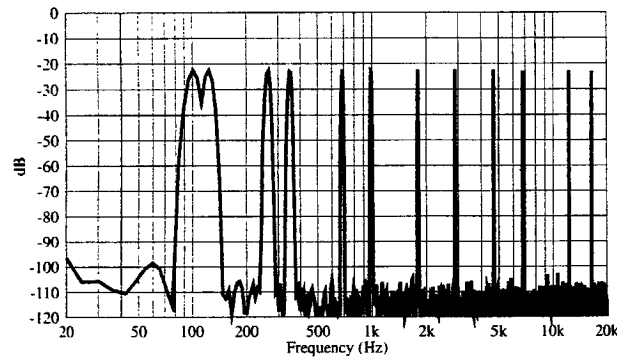


Figure 3

— Lab CD Player Output

Split Band Spectral, 100 Hz & 5 kHz

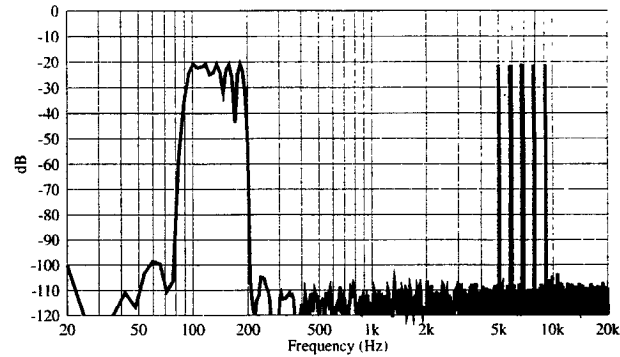


Figure 4

— Lab CD Player Output

Split Band Spectral, 100 Hz & 10 kHz

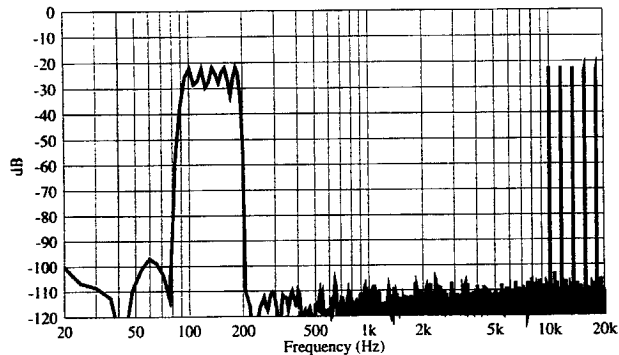


Figure 5

— Lab CD Player Output

Split Band Spectral, 100 Hz & 1.1 kHz

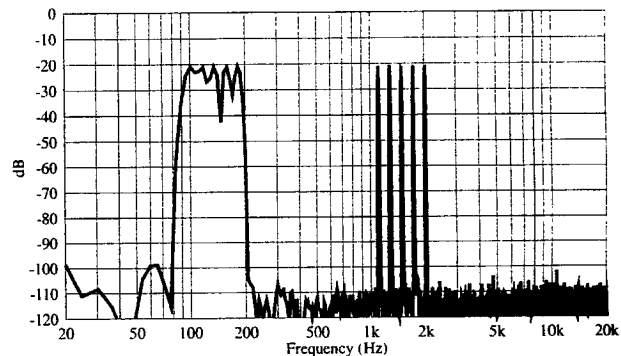


Figure 6

— Lab CD Player Output

Split Band Spectral, 261 Hz & 1.1 kHz

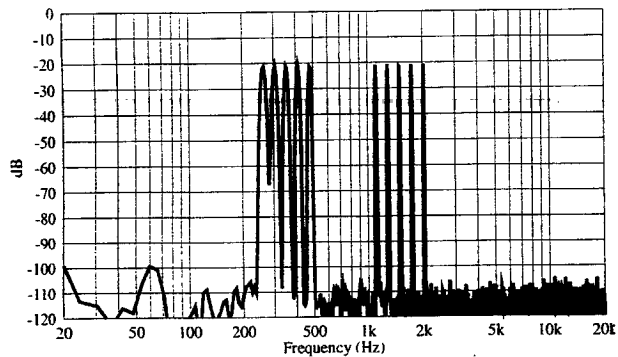


Figure 7

— Lab CD Player Output

Split Band Spectral, 261 Hz & 5 kHz

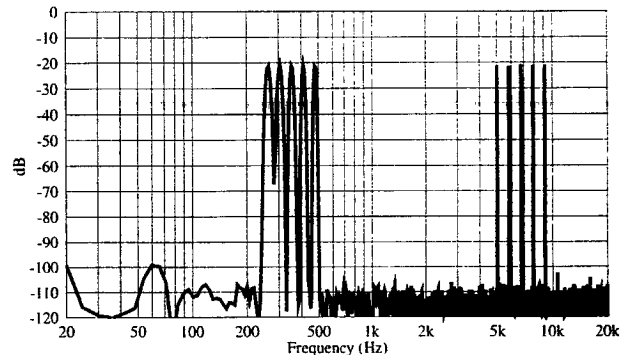


Figure 8

— Lab CD Player Output

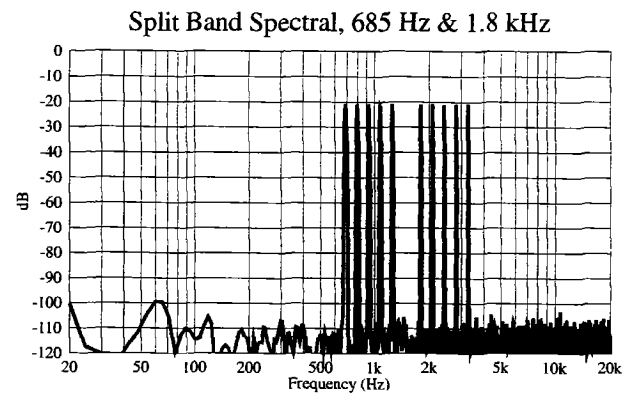


Figure 9

— Lab CD Player Output

Phi6 Spreadsheet

Tone #	Harmonic									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1	100.00	200.00	300.00	400.00	500.00	600.00	700.00	800.00	900.00	1,000.00
2	261.80	523.60	785.40	1,047.20	1,309.00	1,570.80	1,832.60	2,094.40	2,356.20	2,618.00
3	685.41	1,370.82	2,056.23	2,741.64	3,427.05	4,112.46	4,797.87	5,483.28	6,168.69	6,854.10
4	1,794.43	3,588.86	5,383.29	7,177.72	8,972.15	10,766.58	12,561.01	14,355.44	16,149.87	17,944.30
5	4,697.87	9,395.74	14,093.61	18,791.48	23,489.35	28,187.22	32,885.09	37,582.96	42,280.83	46,978.70
6	12,299.20	24,598.40	36,897.60	49,196.80	61,496.00	73,795.20	86,094.40	98,393.60	110,692.80	122,992.00

Intermodulation Products						
Tone #	1	2	3	4	5	6
Subtractive						
1		161.80	585.41	1,694.43	4,597.87	12,199.20
2			423.61	1,532.63	4,436.07	12,037.40
3				1,109.02	4,012.46	11,613.79
4					2,903.44	10,504.77
5						7,601.33
6						

Additive						
1						
2	361.80					
3	785.41	947.21				
4	1,894.43	2,056.23	2,479.84			
5	4,797.87	4,959.67	5,383.28	6,492.30		
6	12,399.20	12,561.00	12,984.61	14,093.63	16,997.07	

Crossmodulation Products						
Tone #	1	2	3	4	5	6
Divisive						
1		2.62	6.85	17.94	46.98	122.99
2			2.62	6.85	17.94	46.98
3				2.62	6.85	17.94
4					2.62	6.85
5						2.62
6						

Multiplicative						
1						
2	26,180.00					
3	68,541.00	179,440.34				
4	179,443.00	469,781.77	#####			
5	469,787.00	#####	#####	#####		
6	#####	#####	#####	#####	#####	

Figure 10

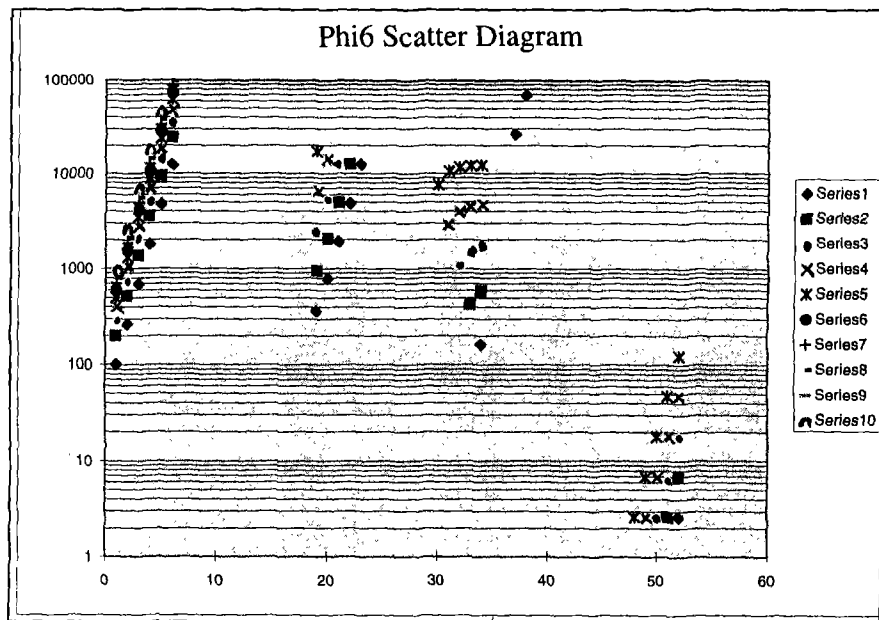


Figure 11

Original Phi12 Spreadsheet

Tone #	Harmonic									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1	100.00	200.00	300.00	400.00	500.00	600.00	700.00	800.00	900.00	1,000.00
2	161.80	323.60	485.40	647.20	809.00	970.80	1,132.60	1,294.40	1,456.20	1,618.00
3	261.80	523.60	785.40	1,047.20	1,309.00	1,570.80	1,832.60	2,094.40	2,356.20	2,618.00
4	423.61	847.22	1,270.83	1,694.44	2,118.05	2,541.66	2,965.27	3,388.88	3,812.49	4,236.10
5	685.41	1,370.82	2,056.23	2,741.64	3,427.05	4,112.46	4,797.87	5,483.28	6,168.69	6,854.10
6	1,109.02	2,218.04	3,327.06	4,436.08	5,545.10	6,654.12	7,763.14	8,872.16	9,981.18	11,090.20
7	1,794.43	3,588.86	5,383.29	7,177.72	8,972.15	10,766.58	12,561.01	14,355.44	16,149.87	17,944.30
8	2,903.44	5,806.88	8,710.32	11,613.76	14,517.20	17,420.64	20,324.08	23,227.52	26,130.96	29,034.40
9	4,697.87	9,395.74	14,093.61	18,791.48	23,489.35	28,187.22	32,885.09	37,582.96	42,280.83	46,978.70
10	7,601.32	15,202.64	22,803.96	30,405.28	38,006.60	45,607.92	53,209.24	60,810.56	68,411.88	76,013.20
11	12,299.20	24,598.40	36,897.60	49,196.80	61,496.00	73,795.20	86,094.40	98,393.60	110,692.80	122,992.00
12	19,900.50	39,801.00	59,701.50	79,602.00	99,502.50	119,403.00	139,303.50	159,204.00	179,104.50	199,005.00

Tone #	Intermodulation Products											
	1	2	3	4	5	6	7	8	9	10	11	12
Subtractive												
1		61.80	161.80	323.61	585.41	1,009.02	1,694.43	2,803.44	4,597.87	7,501.32	12,199.20	19,800.50
2			100.00	261.81	523.61	947.22	1,632.63	2,741.64	4,536.07	7,439.52	12,137.40	19,738.70
3				161.81	423.61	847.22	1,532.63	2,641.64	4,436.07	7,339.52	12,037.40	19,638.70
4					261.80	685.41	1,370.82	2,479.83	4,274.26	7,177.71	11,875.59	19,476.89
5						423.61	1,109.02	2,218.03	4,012.46	6,915.91	11,813.79	19,215.09
6							685.41	1,794.42	3,588.85	6,492.30	11,190.18	18,791.48
7								1,109.01	2,903.44	5,806.89	10,504.77	18,106.07
8									1,794.43	4,697.88	9,395.76	16,997.06
9										2,903.45	7,601.33	15,202.63
10											4,697.88	12,299.18
11												7,601.30
12												
Additive												
1												
2	261.80											
3	361.80	423.60										
4	523.61	585.41	685.41									
5	785.41	847.21	947.21	1,109.02								
6	1,209.02	1,270.82	1,370.82	1,532.63	1,794.43							
7	1,894.43	1,956.23	2,056.23	2,218.04	2,479.84	2,903.45						
8	3,003.44	3,065.24	3,165.24	3,327.05	3,588.85	4,012.46	4,697.87					
9	4,797.87	4,859.67	4,959.67	5,121.48	5,383.28	5,806.89	6,492.30	7,601.31				
10	7,701.32	7,763.12	7,863.12	8,024.93	8,286.73	8,710.34	9,395.75	10,504.76	12,299.19			
11	12,399.20	12,461.00	12,561.00	12,722.81	12,984.61	13,408.22	14,093.63	15,202.64	16,997.07	19,900.52		
12	20,000.50	20,062.30	20,162.30	20,324.11	20,585.91	21,009.52	21,694.93	22,803.94	24,598.37	27,501.82	32,199.70	

Tone #	Crossmodulation Products											
	1	2	3	4	5	6	7	8	9	10	11	12
Divisive												
1		1.62	2.52	4.24	6.85	11.09	17.94	29.03	46.98	76.01	122.99	199.01
2			1.62	2.62	4.24	6.85	11.09	17.94	29.04	46.98	76.01	122.99
3				1.62	2.62	4.24	6.85	11.09	17.94	29.03	46.98	76.01
4					1.62	2.62	4.24	6.85	11.09	17.94	29.03	46.98
5						1.62	2.62	4.24	6.85	11.09	17.94	29.03
6							1.62	2.62	4.24	6.85	11.09	17.94
7								1.62	2.62	4.24	6.85	11.09
8									1.62	2.62	4.24	6.85
9										1.62	2.62	4.24
10											1.62	2.62
11												1.62
12												
Multiplicative												
1												
2	16,180.00											
3	26,180.00	42,359.24										
4	42,361.00	68,540.10	110,901.10									
5	68,541.00	110,899.34	179,440.34	290,346.53								
6	110,902.00	179,439.44	290,341.44	469,791.96	760,133.40							
7	179,443.00	290,338.77	469,781.77	760,138.49	*****	*****						
8	290,344.00	469,776.59	760,120.59	*****	*****	*****	*****					
9	469,787.00	760,115.37	*****	*****	*****	*****	*****	*****				
10	760,132.00	*****	*****	*****	*****	*****	*****	*****	*****			
11	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****		
12	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	

Figure 12

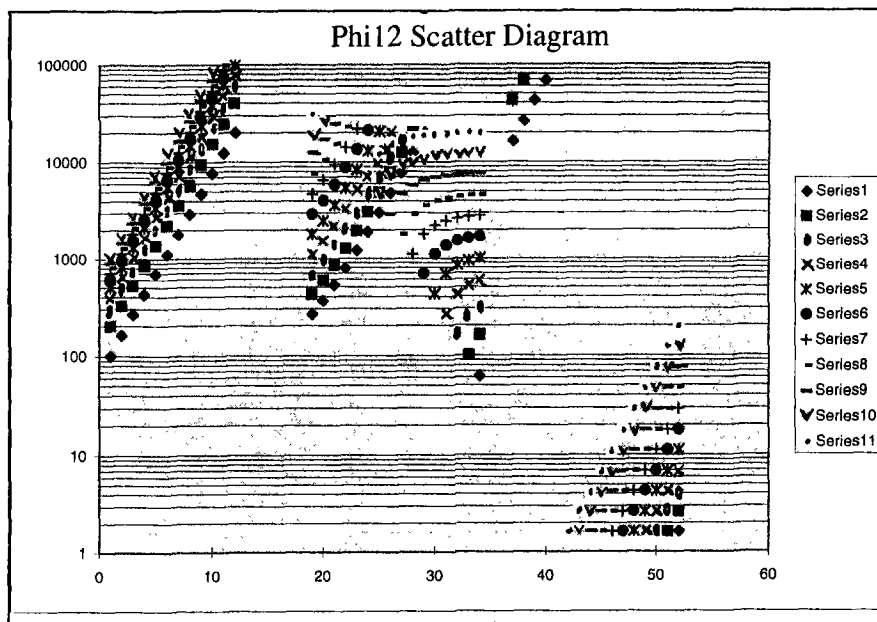


Figure 13

Phi 12r Spreadsheet

Tone #	Harmonic									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1	100.00	200.00	300.00	400.00	500.00	600.00	700.00	800.00	900.00	1,000.00
2	122.00	244.00	366.00	488.00	610.00	732.00	854.00	976.00	1,098.00	1,220.00
3	261.80	523.60	785.40	1,047.20	1,309.00	1,570.80	1,832.60	2,094.40	2,356.20	2,618.00
4	348.19	696.38	1,044.57	1,392.76	1,740.95	2,089.14	2,437.33	2,785.52	3,133.71	3,481.90
5	685.41	1,370.82	2,056.23	2,741.64	3,427.05	4,112.46	4,797.87	5,483.28	6,168.69	6,854.10
6	986.99	1,973.98	2,960.97	3,947.96	4,934.95	5,921.94	6,908.93	7,895.92	8,882.91	9,869.90
7	1,794.43	3,588.86	5,383.29	7,177.72	8,972.15	10,766.58	12,561.01	14,355.44	16,149.87	17,944.30
8	2,871.09	5,742.18	8,613.27	11,484.36	14,355.45	17,226.54	20,097.63	22,968.72	25,839.81	28,710.90
9	4,697.87	9,395.74	14,093.61	18,791.48	23,489.35	28,187.22	32,885.09	37,582.96	42,280.83	46,978.70
10	6,764.93	13,529.86	20,294.79	27,059.72	33,824.65	40,589.58	47,354.51	54,119.44	60,884.37	67,649.30
11	12,299.20	24,598.40	36,897.60	49,196.80	61,496.00	73,795.20	86,094.40	98,393.60	110,692.80	122,992.00
12	16,357.90	32,715.80	49,073.70	65,431.60	81,789.50	98,147.40	114,505.30	130,863.20	147,221.10	163,579.00

Tone #	Intermodulation Products											
	1	2	3	4	5	6	7	8	9	10	11	12
Subtractive												
1		22.00	161.80	248.19	585.41	886.99	1,694.43	2,771.09	4,597.87	6,664.93	12,199.20	16,257.90
2			138.80	226.19	563.41	864.99	1,672.43	2,749.09	4,575.87	6,642.93	12,177.20	16,235.90
3				86.39	423.61	725.19	1,532.63	2,609.29	4,436.07	6,503.13	12,037.40	16,096.10
4					337.22	638.80	1,446.24	2,522.90	4,349.68	6,416.74	11,951.01	16,009.71
5						301.58	1,109.02	2,185.68	4,012.46	6,079.52	11,613.79	15,672.49
6							807.44	1,884.10	3,710.88	5,777.94	11,312.21	15,370.91
7								1,076.66	2,903.44	4,970.50	10,504.77	14,563.47
8									1,826.78	3,893.84	9,428.11	13,486.81
9										2,067.06	7,601.33	11,660.03
10											5,534.27	9,592.97
11												4,058.70
12												

Tone #	Additive											
	1	2	3	4	5	6	7	8	9	10	11	12
1												
2	222.00											
3	361.80	383.80										
4	448.19	470.19	609.99									
5	785.41	807.41	947.21	1,033.60								
6	1,086.99	1,108.99	1,248.79	1,335.18	1,672.40							
7	1,894.43	1,916.43	2,056.23	2,142.62	2,479.84	2,781.42						
8	2,971.09	2,993.09	3,132.89	3,219.28	3,556.50	3,858.08	4,665.52					
9	4,797.87	4,819.87	4,959.67	5,046.06	5,383.28	5,684.86	6,492.30	7,568.96				
10	6,864.93	6,886.93	7,026.73	7,113.12	7,450.34	7,751.92	8,559.36	9,636.02	11,462.80			
11	12,399.20	12,421.20	12,561.00	12,647.39	12,984.61	13,286.19	14,093.63	15,170.29	16,997.07	19,064.13		
12	16,457.90	16,479.90	16,619.70	16,706.09	17,043.31	17,344.89	18,152.33	19,228.99	21,055.77	23,122.83	26,657.10	

Tone #	Crossmodulation Products											
	1	2	3	4	5	6	7	8	9	10	11	12
Divisive												
1		1.22	2.62	3.48	6.85	9.87	17.94	28.71	46.98	67.65	122.99	163.58
2			2.15	2.85	5.62	8.09	14.71	23.53	38.51	55.45	100.81	134.08
3				1.33	2.62	3.77	6.85	10.97	17.94	25.84	46.98	62.48
4					1.97	2.83	5.15	8.25	13.49	19.43	35.32	46.98
5						1.44	2.62	4.19	6.85	9.87	17.94	23.87
6							1.82	2.91	4.76	6.85	12.46	16.57
7								1.60	2.62	3.77	6.85	9.12
8									1.64	2.36	4.28	5.70
9										1.44	2.62	3.48
10											1.82	2.42
11												1.33
12												

Tone #	Multiplicative											
	1	2	3	4	5	6	7	8	9	10	11	12
1												
2	12,200.00											
3	26,180.00	31,939.60										
4	34,819.00	42,479.18	91,156.14									
5	68,541.00	83,620.02	179,440.34	238,652.91								
6	98,899.00	120,412.78	258,393.98	343,660.05	676,492.82							
7	179,443.00	218,920.46	469,781.77	624,802.58	*****	*****						
8	287,109.00	350,272.98	751,651.36	999,684.83	*****	*****	*****					
9	469,787.00	573,140.14	*****	*****	*****	*****	*****	*****				
10	676,493.00	825,321.46	*****	*****	*****	*****	*****	*****	*****			
11	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****		
12	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	

Figure 14

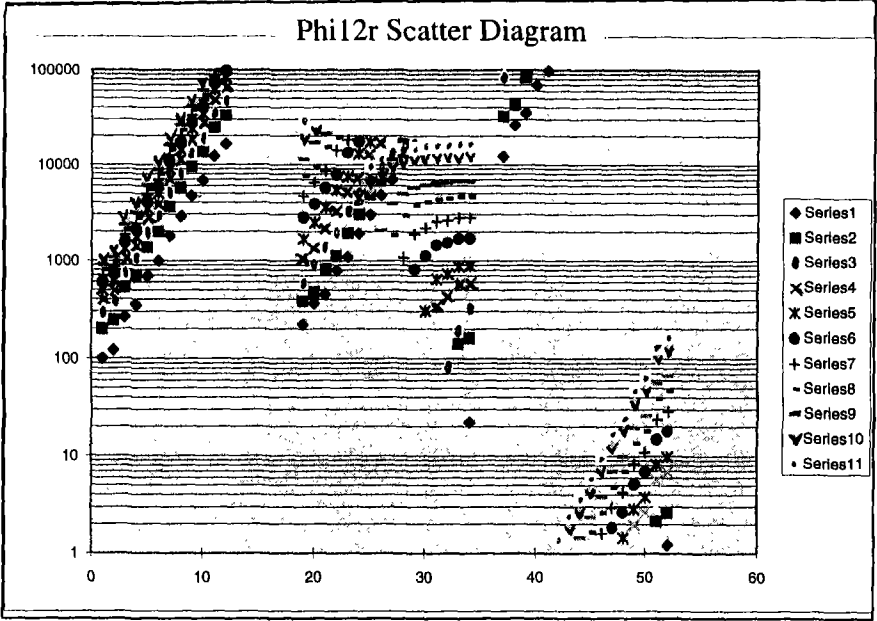


Figure 15

Split Band Spreadsheet

Tone #	1st	2nd	3rd	4th	Harmonic		7th	8th	9th	10th
1	100.00	200.00	300.00	400.00	500.00	600.00	700.00	800.00	900.00	1,000.00
2	116.18	232.36	348.54	464.72	580.90	697.08	813.26	929.44	1,045.62	1,161.80
3	134.98	269.96	404.94	539.92	674.90	809.88	944.86	1,079.84	1,214.82	1,349.80
4	156.80	313.60	470.40	627.20	784.00	940.80	1,097.60	1,254.40	1,411.20	1,568.00
5	182.19	364.38	546.57	728.76	910.95	1,093.14	1,275.33	1,457.52	1,639.71	1,821.90
6	5,000.00	10,000.00	15,000.00	20,000.00	25,000.00	30,000.00	35,000.00	40,000.00	45,000.00	50,000.00
7	5,809.01	11,618.02	17,427.03	23,236.04	29,045.05	34,854.06	40,663.07	46,472.08	52,281.09	58,090.10
8	6,748.94	13,497.88	20,246.82	26,995.76	33,744.70	40,493.64	47,242.58	53,991.52	60,740.46	67,489.40
9	7,840.94	15,681.88	23,522.82	31,363.76	39,204.70	47,045.64	54,886.58	62,727.52	70,568.46	78,409.40
10	9,109.63	18,219.26	27,328.89	36,438.52	45,548.15	54,657.78	63,767.41	72,877.04	81,986.67	91,096.30

Tone #	1	2	3	4	5	6	7	8	9	10
Intermodulation Products										
Subtractive										
1		16.18	34.98	56.80	82.19	4,900.00	5,709.01	6,648.94	7,740.94	9,009.63
2			18.80	40.62	66.01	4,883.82	5,692.83	6,632.76	7,724.76	8,993.45
3				21.82	47.21	4,865.02	5,674.03	6,613.96	7,705.96	8,974.65
4					25.39	4,843.20	5,652.21	6,592.14	7,684.14	8,952.83
5						4,817.81	5,626.82	6,566.75	7,658.75	8,927.44
6							809.01	1,748.94	2,840.94	4,109.63
7								939.93	2,031.93	3,300.62
8									1,092.00	2,360.69
9										1,268.69
10										

Tone #	1	2	3	4	5	6	7	8	9	10
Additive										
1										
2	216.18									
3	234.98	251.16								
4	256.80	272.98	291.78							
5	282.19	298.37	317.17	338.99						
6	5,100.00	5,116.18	5,134.98	5,156.80	5,182.19					
7	5,909.01	5,925.19	5,943.99	5,965.81	5,991.20	10,809.01				
8	6,848.94	6,865.12	6,883.92	6,905.74	6,931.13	11,748.94	12,557.95			
9	7,940.94	7,957.12	7,975.92	7,997.74	8,023.13	12,840.94	13,649.95	14,589.88		
10	9,209.63	9,225.81	9,244.61	9,266.43	9,291.82	14,109.63	14,918.64	15,858.57	16,950.57	

Tone #	1	2	3	4	5	6	7	8	9	10
Crossmodulation Products										
Divisive										
1		1.16	1.35	1.57	1.82	50.00	58.09	67.49	78.41	91.10
2			1.16	1.35	1.57	43.04	50.00	58.09	67.49	78.41
3				1.16	1.35	37.04	43.04	50.00	58.09	67.49
4					1.16	31.89	37.05	43.04	50.01	58.10
5						27.44	31.88	37.04	43.04	50.00
6							1.16	1.35	1.57	1.82
7								1.16	1.35	1.57
8									1.16	1.35
9										1.16
10										

Tone #	1	2	3	4	5	6	7	8	9	10
Multiplicative										
1										
2	11,618.00									
3	13,498.00	15,681.98								
4	15,680.00	18,217.02	21,164.86							
5	18,219.00	21,166.83	24,592.01	28,567.39						
6	500,000.00	580,900.00	674,900.00	784,000.00	910,950.00					
7	580,901.00	674,890.78	784,100.17	910,852.77	*****	*****				
8	674,894.00	784,091.85	910,971.92	*****	*****	*****	*****			
9	784,094.00	910,960.41	*****	*****	*****	*****	*****	*****		
10	910,963.00	*****	*****	*****	*****	*****	*****	*****	*****	

Figure 16

Split Band Spectral, 100 Hz & 4.7 kHz

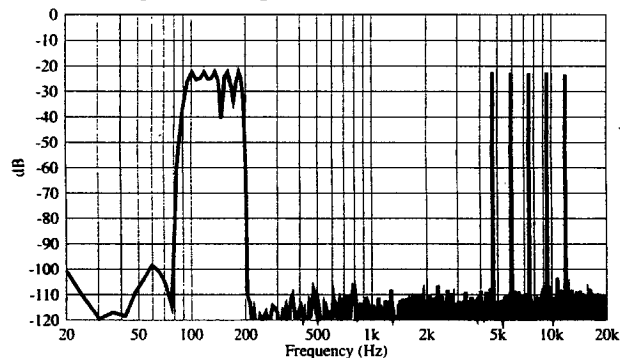


Figure 17

Split Band Spectral, 100 Hz & 987 Hz

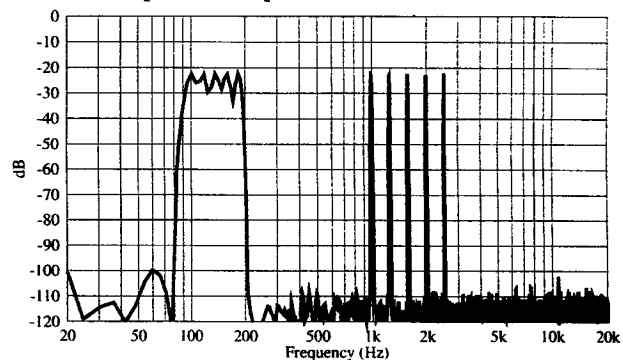


Figure 18

Tri-Band Spectral

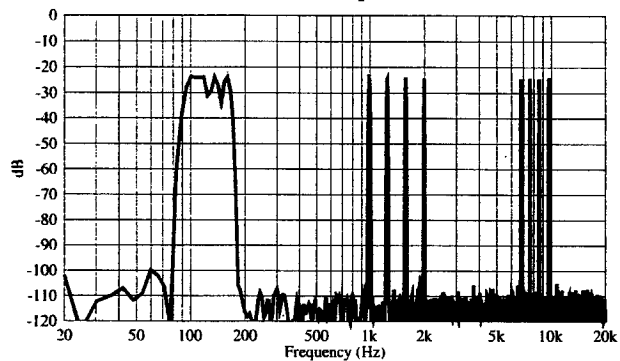


Figure 19

Consumer CD Player, Phi12r

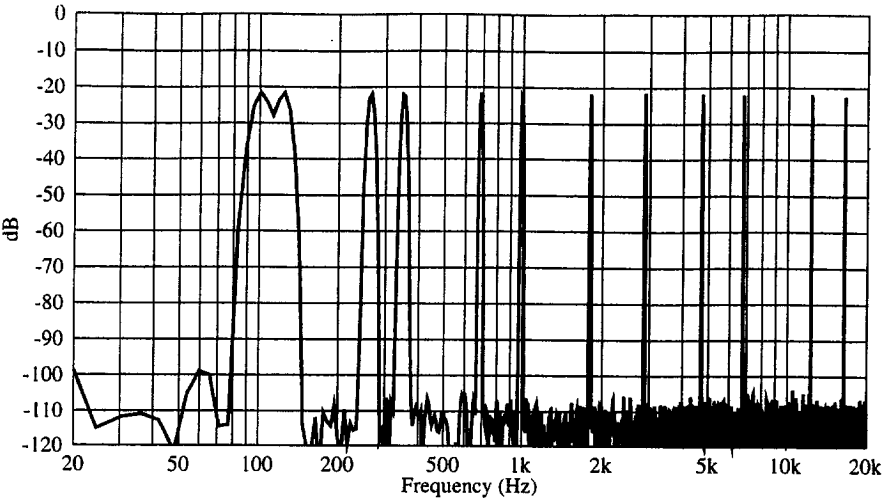


Figure 20

— CD player Output

Comparison: Line vs. Headphone Out

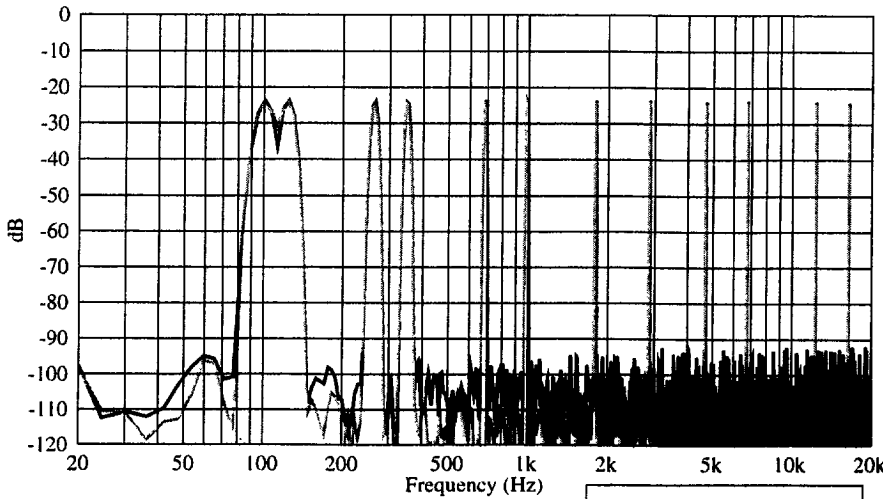


Figure 21

— Headphone Out
- - - Line Out

CD Player Showing Distortion, Phi12r

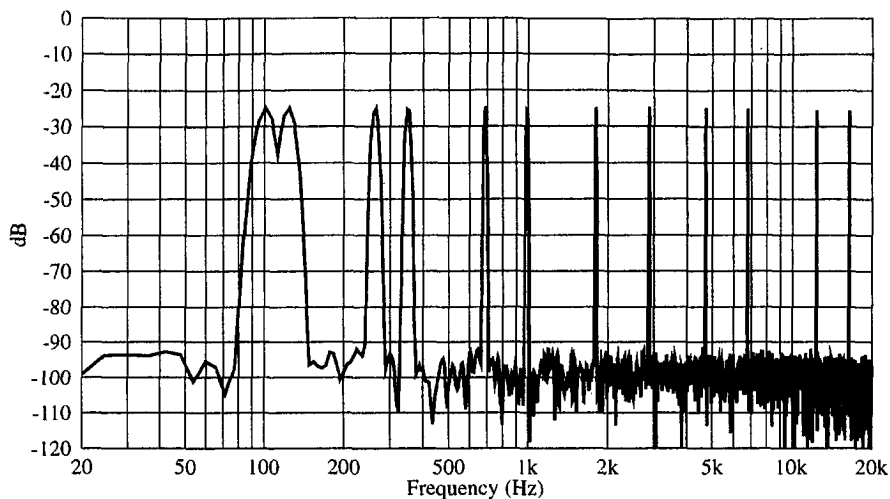


Figure 22

— CD player Output

Comparison: 0dbFS vs -6 dB Recorded Levels

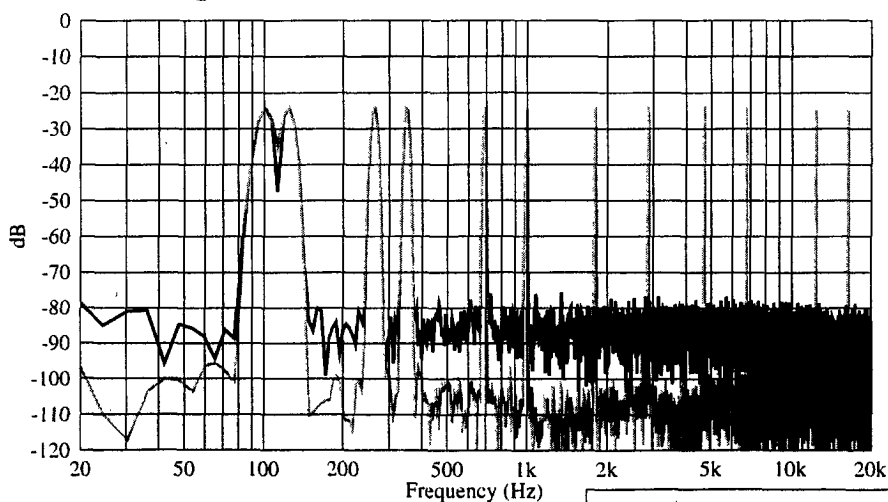


Figure 23

— 0 dbFS Recorded Level
— -6 dB Recorded Level

Consumer Cassette Deck, Phi12r

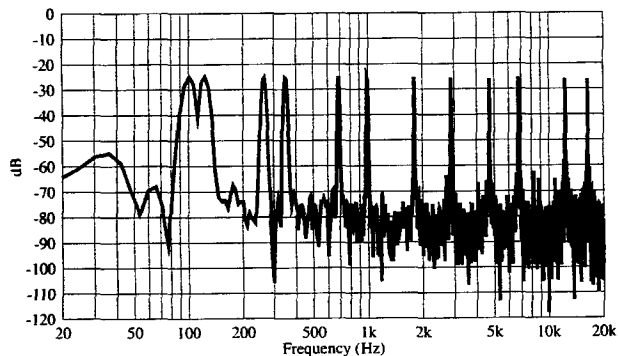


Figure 24

— Cassette Deck Output

Consumer Cassette Deck, Low-High Spectral

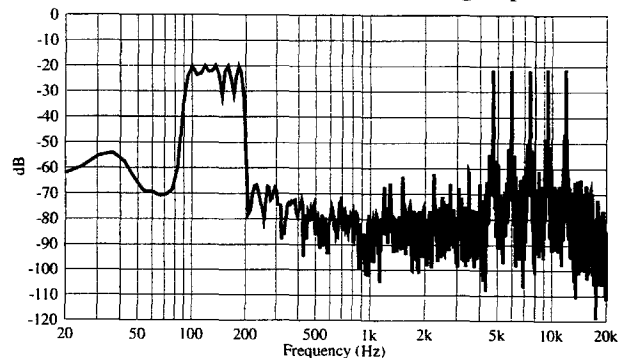


Figure 25

— Cassette Deck Output

Consumer Cassette Deck, Low-Mid Spectral

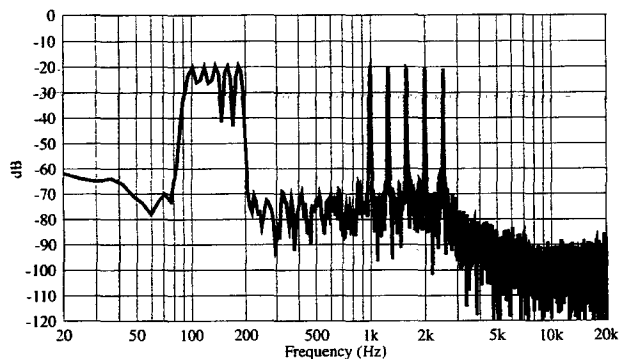


Figure 26

— Cassette Deck Output

Consumer Cassette Deck, Tri-Band Spectral

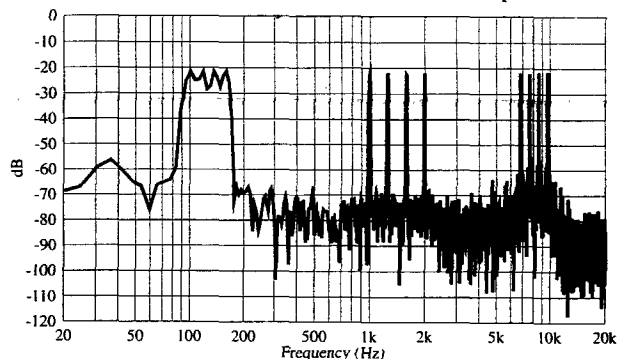


Figure 27

— Cassette Deck Output

Consumer Mini-Disc Deck, Phi12r Spectral

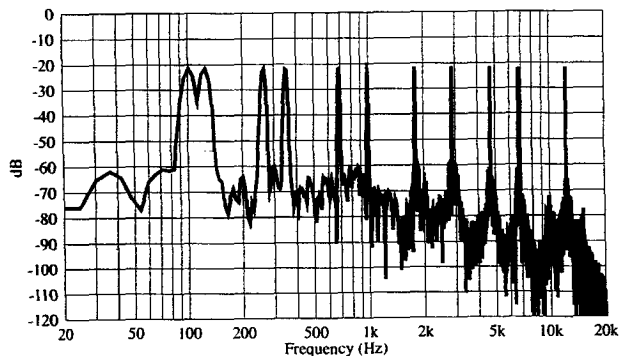


Figure 28

— MD Deck Output

Mini-Disc Deck, Split Band Low-High Spectral

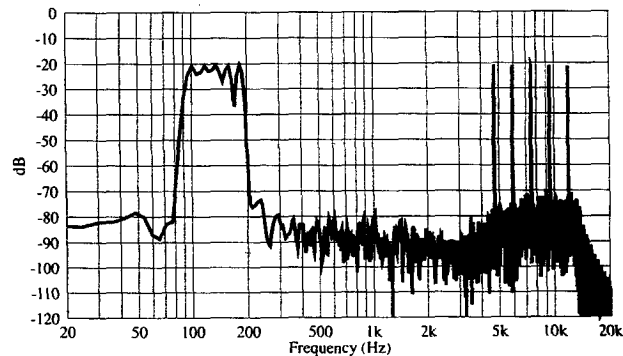


Figure 29

— MD Deck Output

Mini-Disc Deck, Split Band Low-mid Spectral

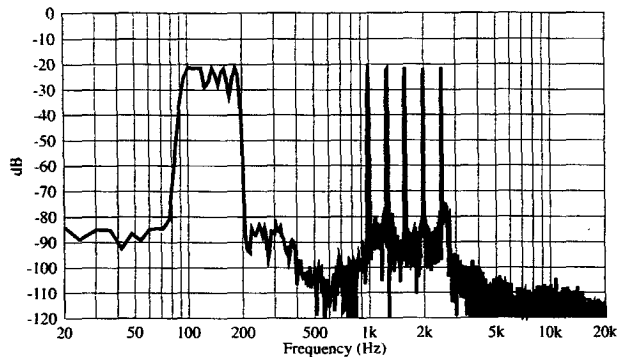


Figure 30

— MD Deck Output

Mini-Disc Deck, Tri-Band Spectral

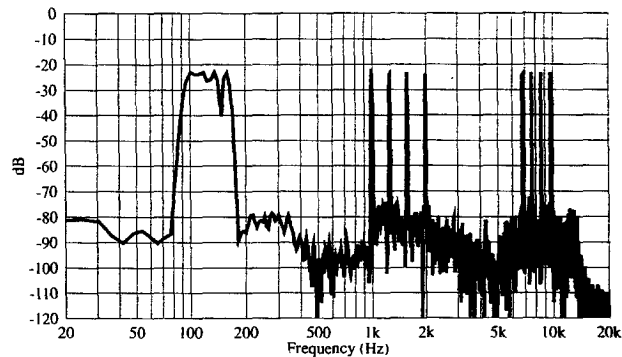


Figure 31

— MD Deck Output

Mini-Disc Deck, Split Band Spectral

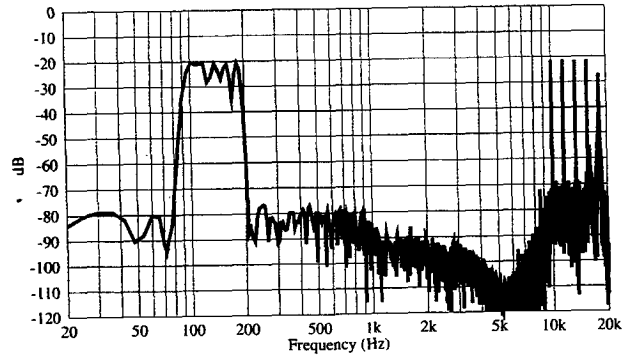


Figure 32

— MD Deck Output

Digital Filter/Delay, Phi12r

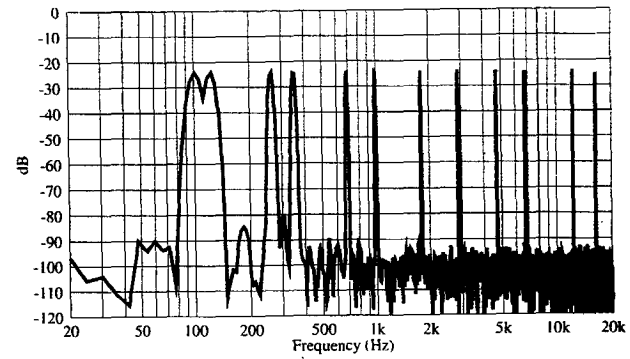


Figure 33

— Digital Filter Output

Digital Filter, Filter Engaged, Phi12r

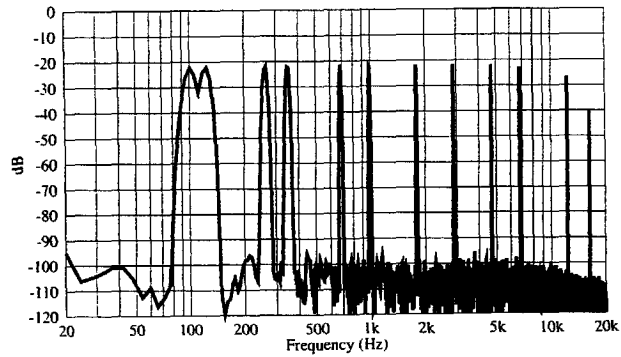


Figure 34

— Digital Filter Output

Speaker A, Phi6 Spectral

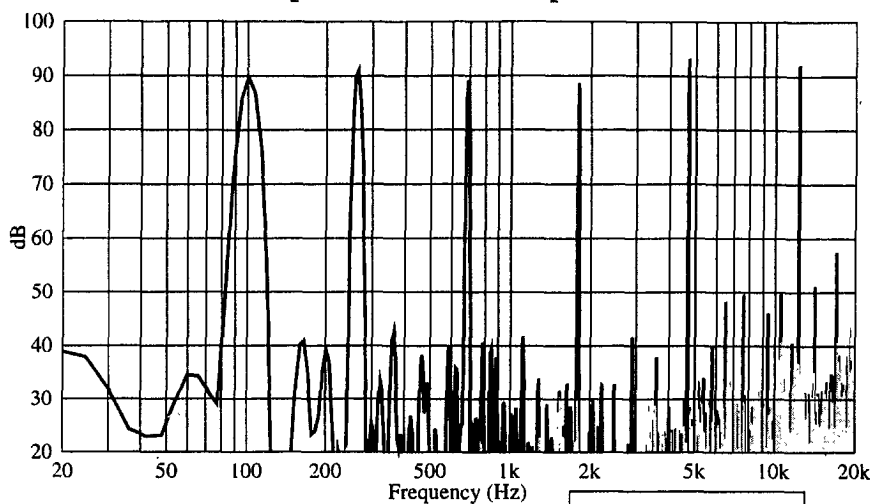


Figure 35

— Speaker A
— Noise Floor

Speaker A, Phi6 Spectral, 10W

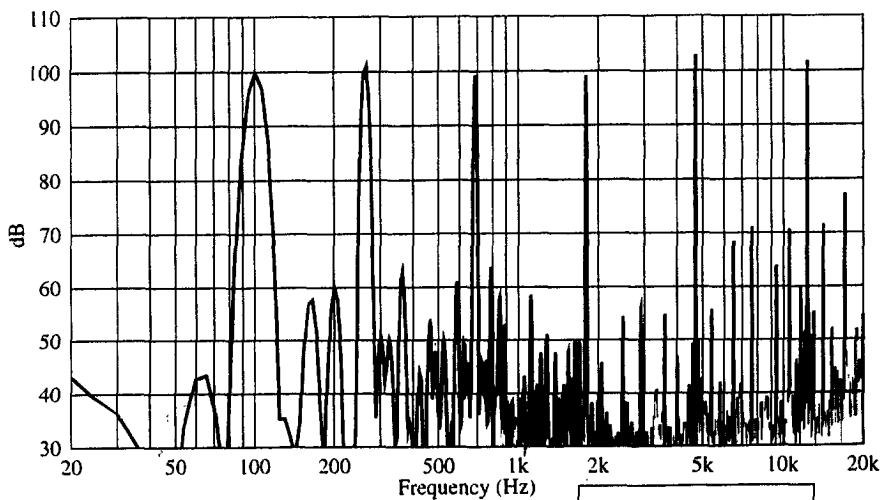


Figure 36

— Speaker A
— Noise Floor

Speaker A, Phi12r Spectral, 10W

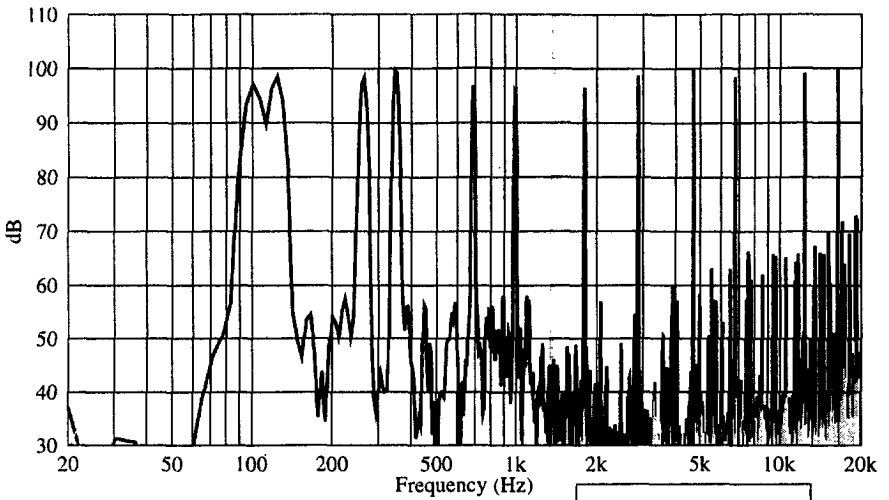


Figure 37

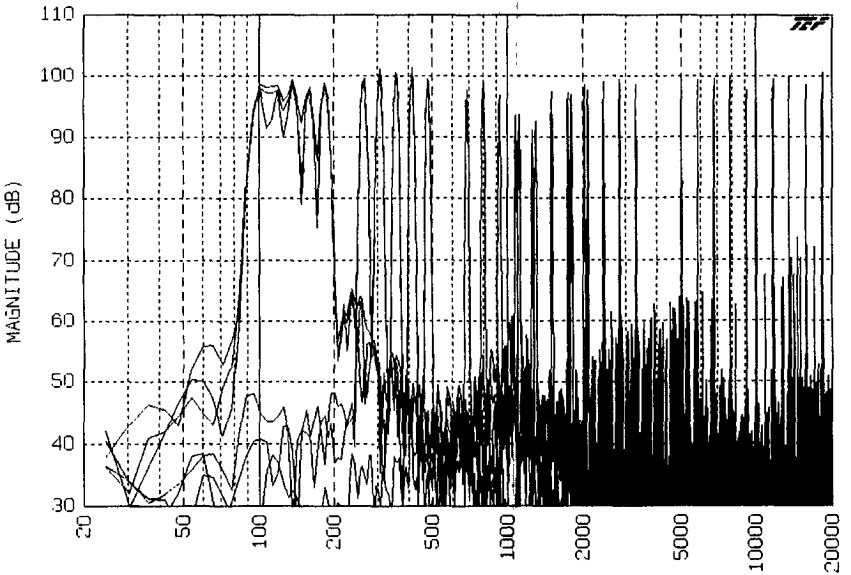
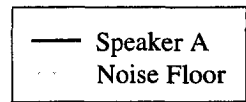
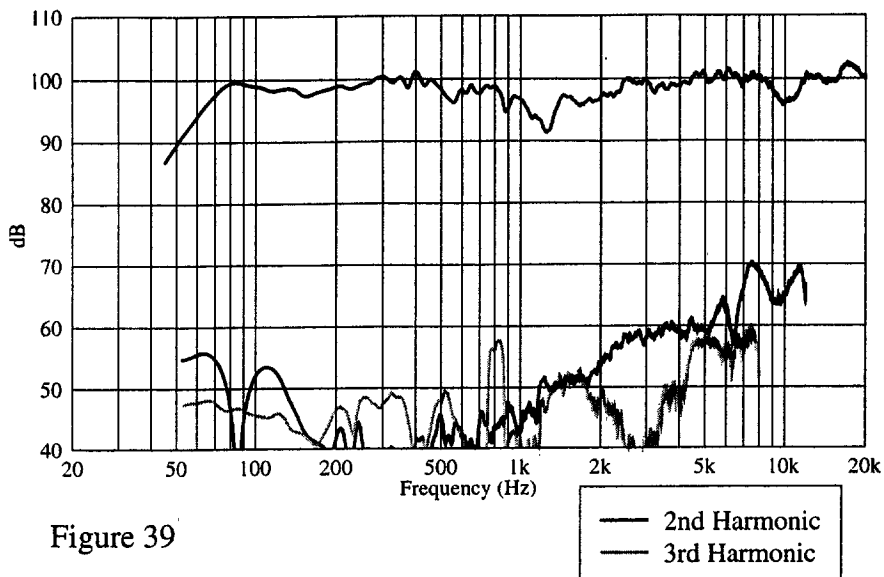
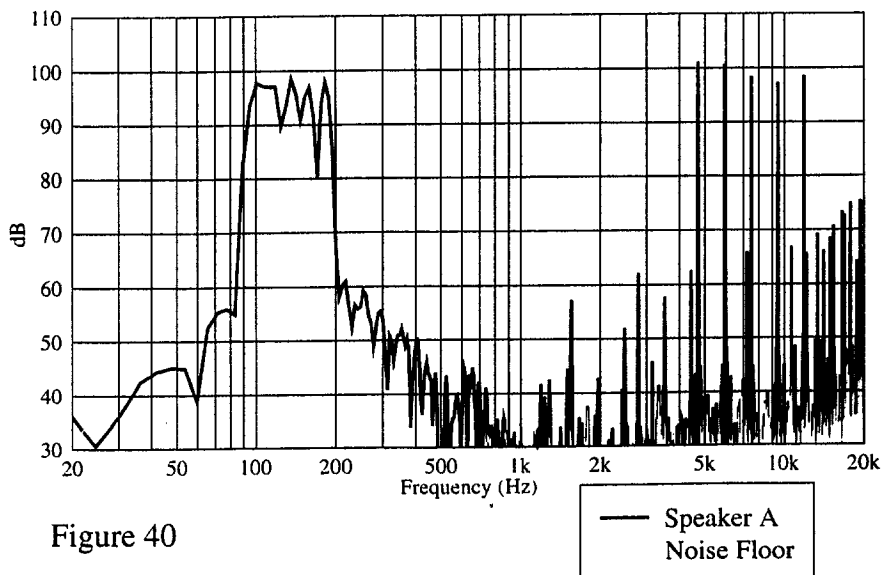


Figure 38

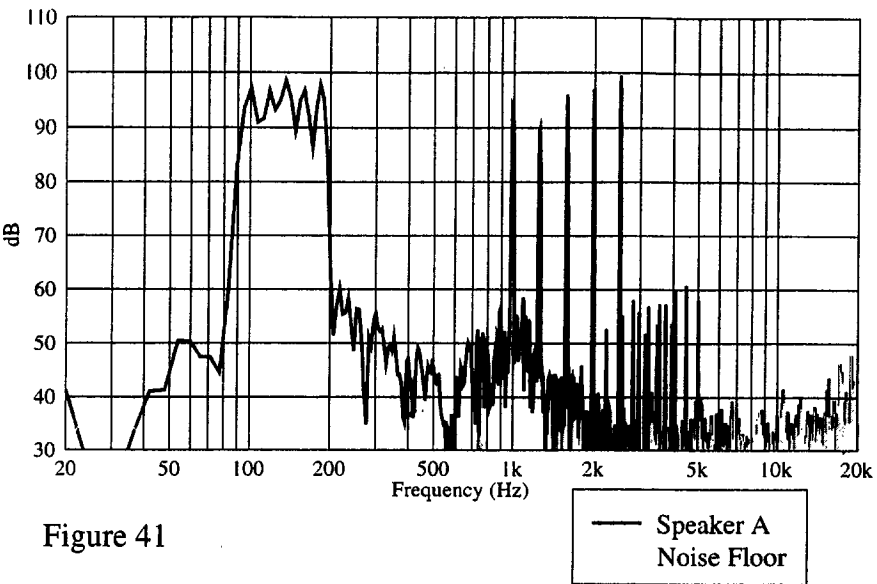
Harmonic Distortion Speaker A



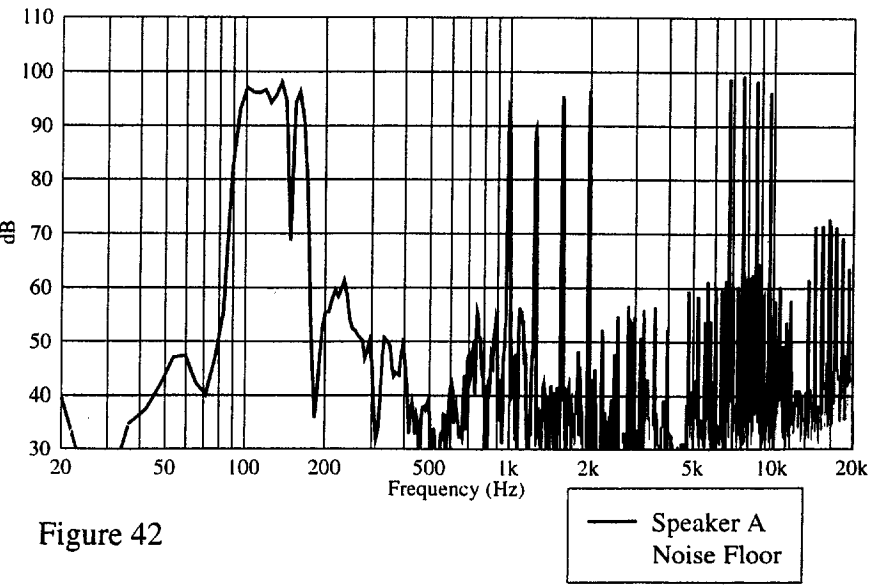
Spkr A, Split Band 100 Hz & 4.7 kHz Spectral, 10W



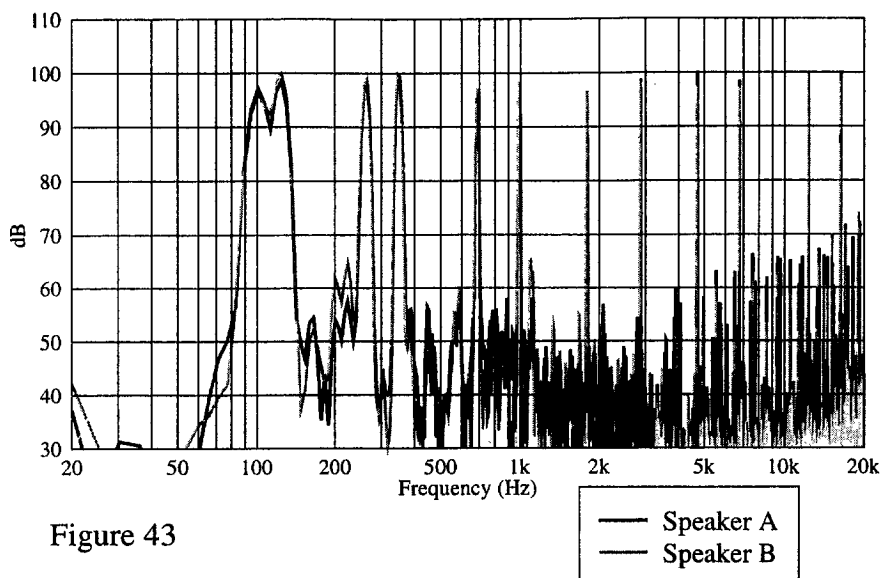
Spkr A, Split Band 100 Hz & 1.1 kHz Spectral, 10W



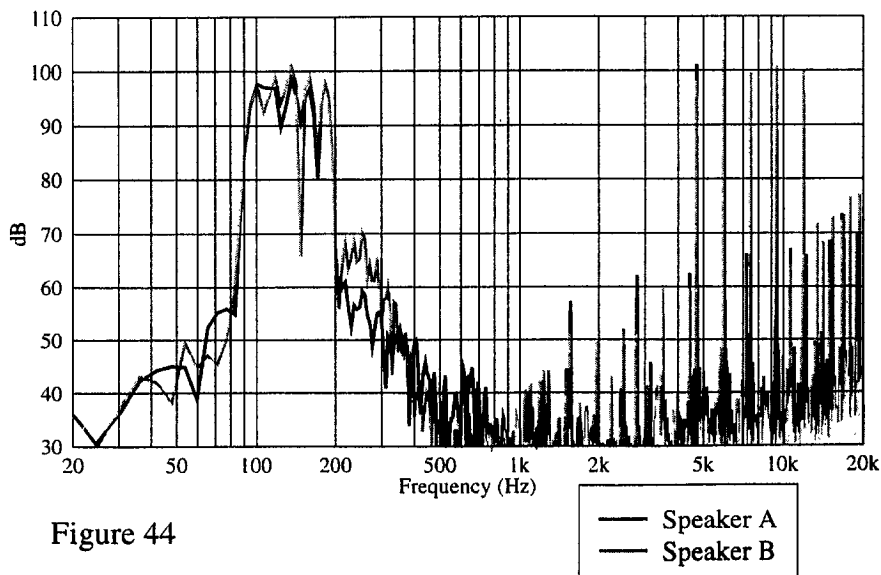
Spkr A, Tri-Band Spectral, 10W



Comparison: Spkr A vs. Spkr B, Phi12r, 10W



Spkr A vs Spkr B, Split Band 100Hz & 4.7kHz, 10W



Spkr A vs Spkr B, Split Band 100 Hz & 1.1 kHz, 10W

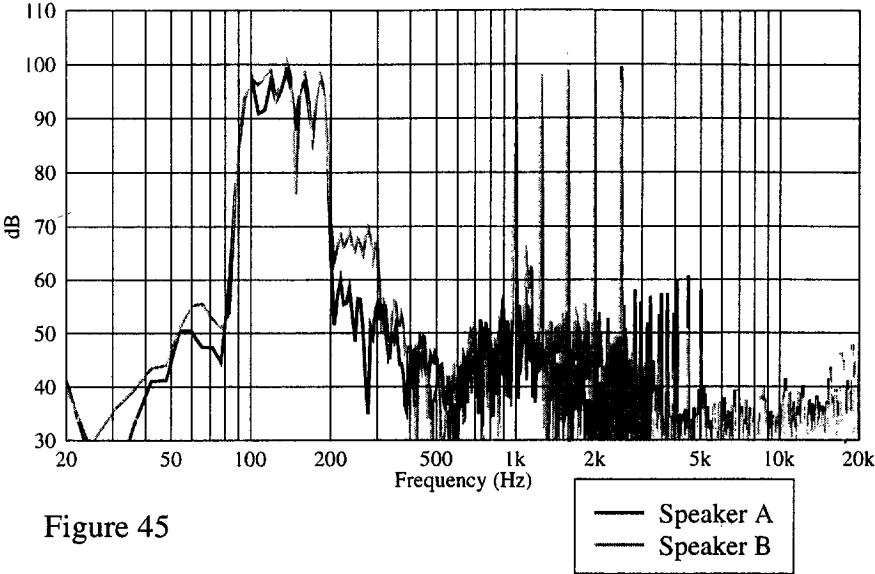


Figure 45

Spkr A vs Spkr B, Tri-Band Spectral, 10W

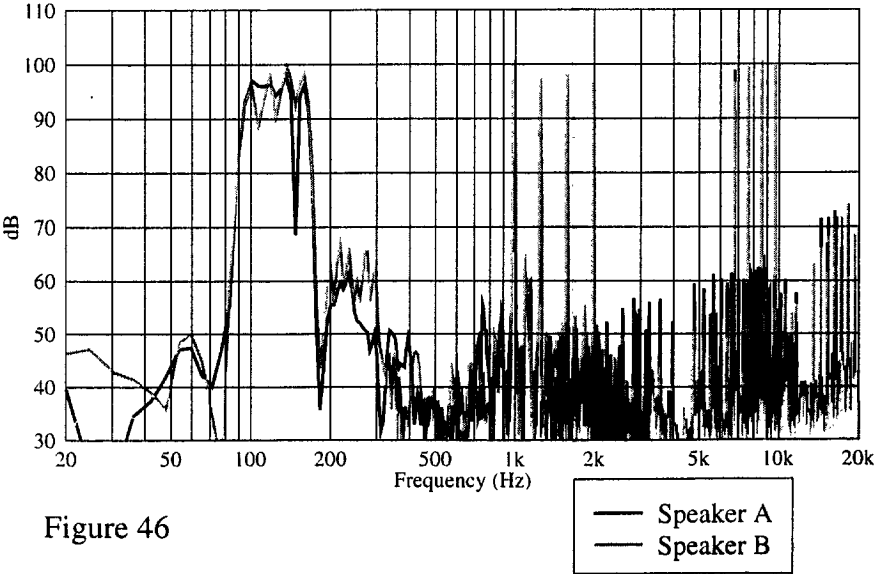


Figure 46

Prototype Studio Monitor, Phi12r, 1W

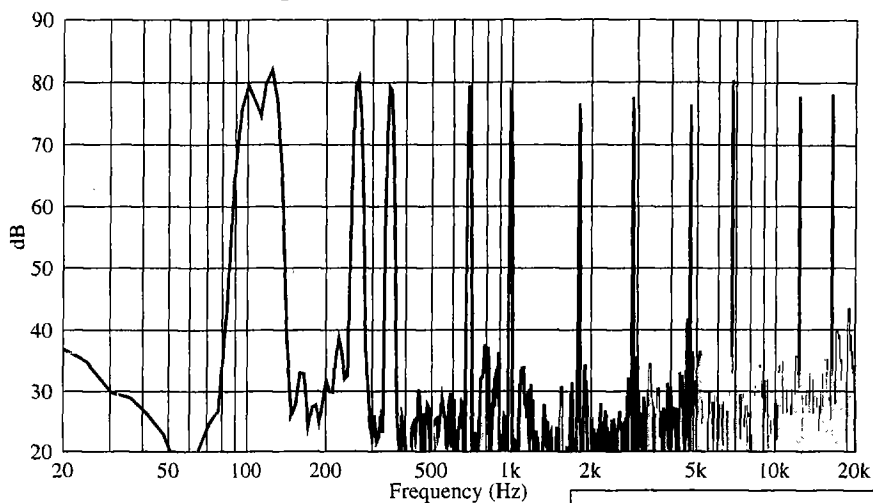


Figure 47

— Studio Monitor Output
Noise Floor

Prototype Studio Monitor, Split Band 100Hz & 4.7kHz, 1W

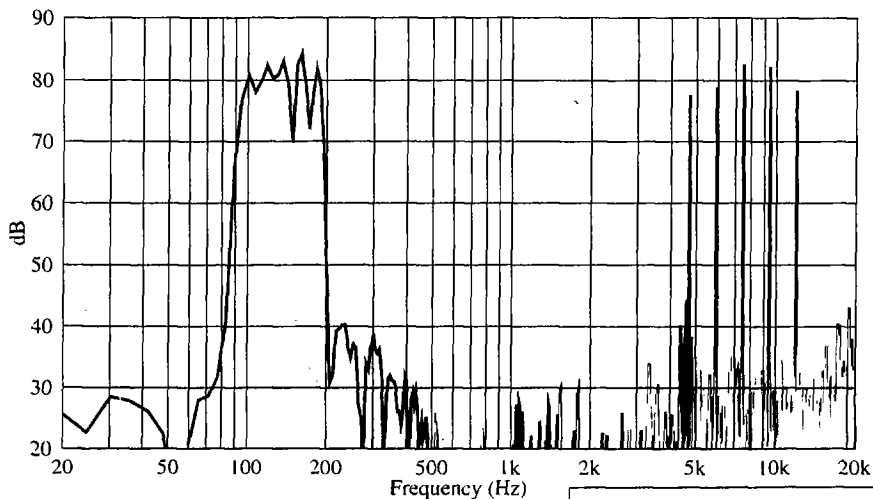
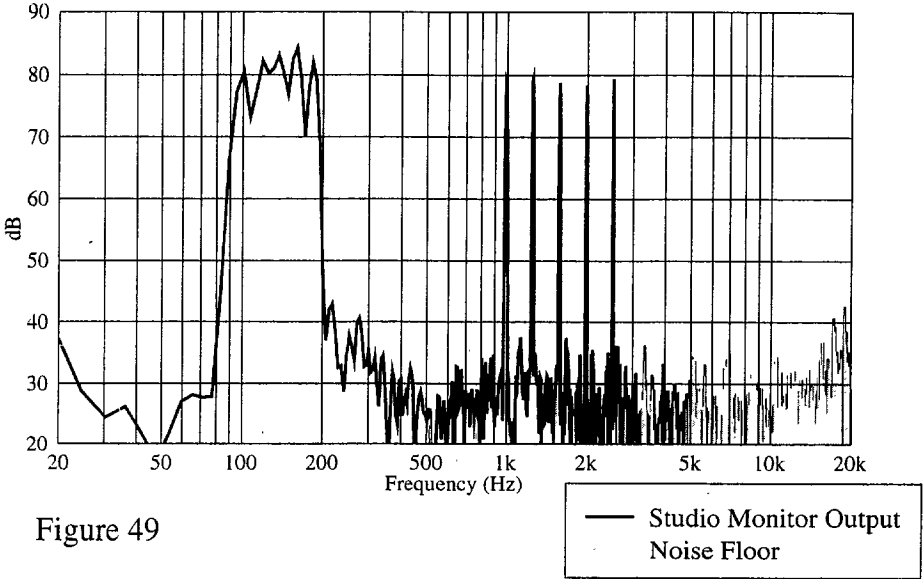


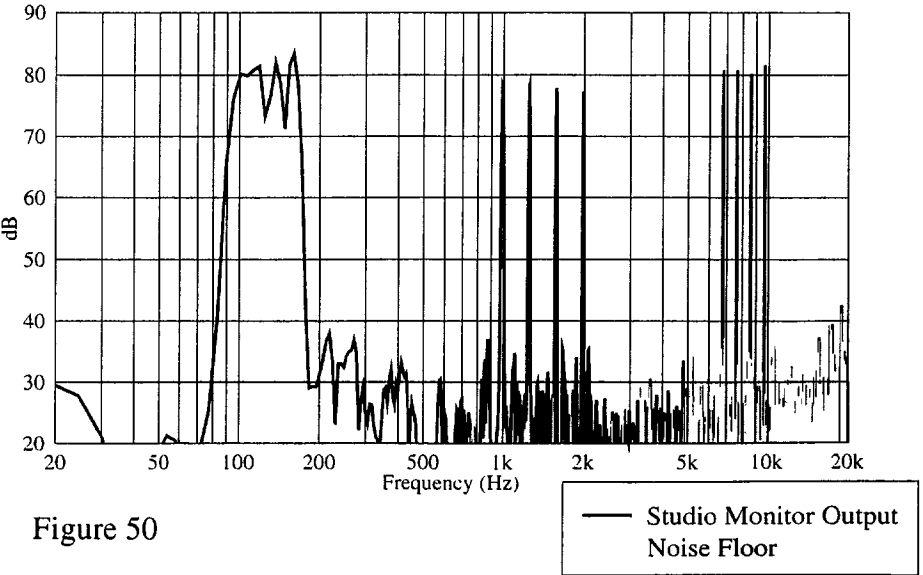
Figure 48

— Studio Monitor Output
Noise Floor

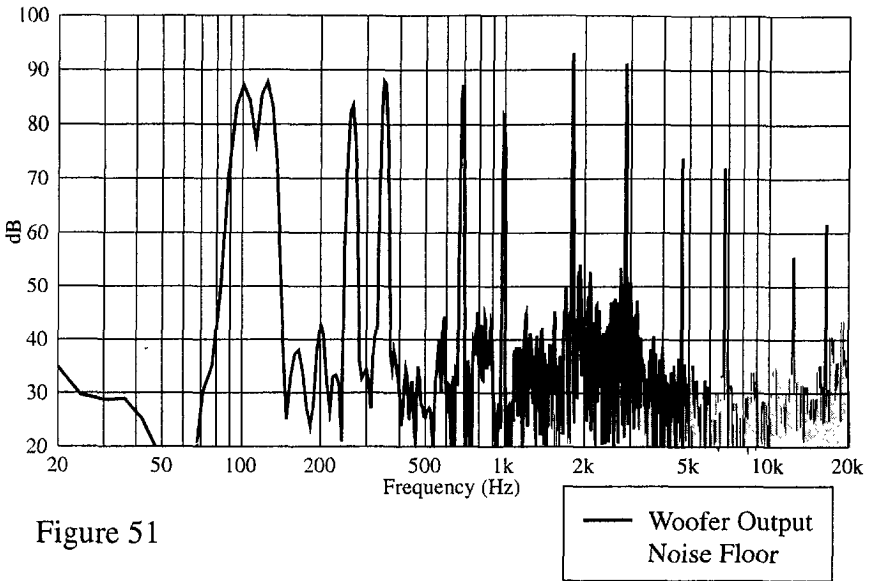
Prototype Studio Monitor, Split Band 100Hz & 1.1kHz, 1W



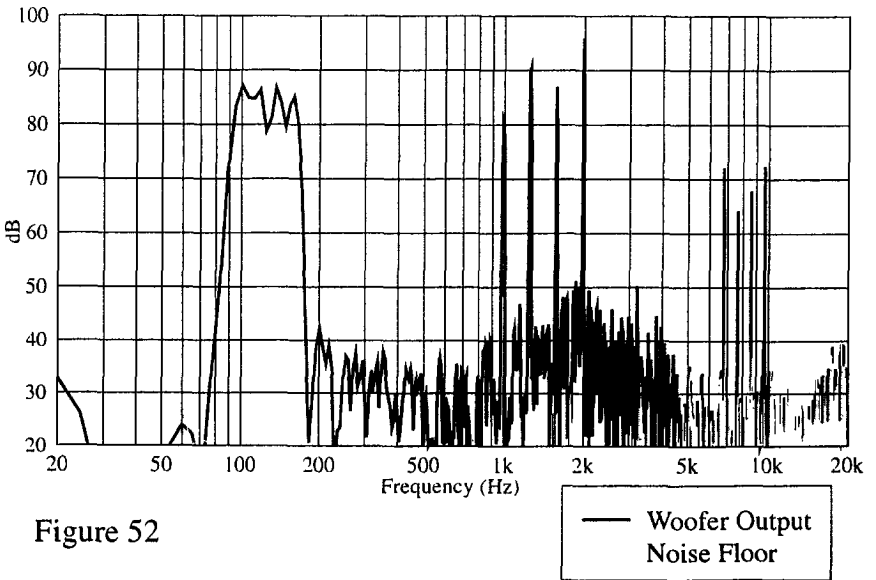
Prototype Studio Monitor, Tri-Band Spectral, 1W



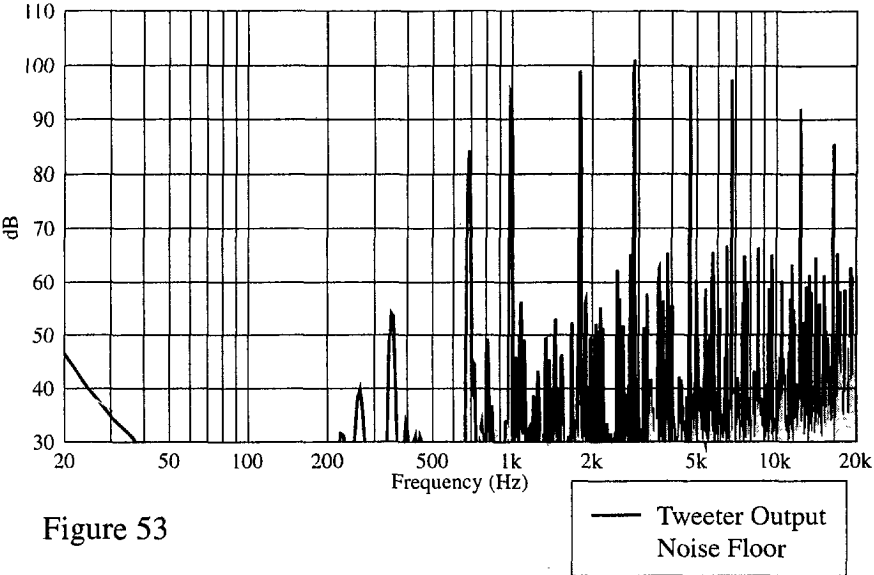
Woofer Phi12r Spectral, 1W



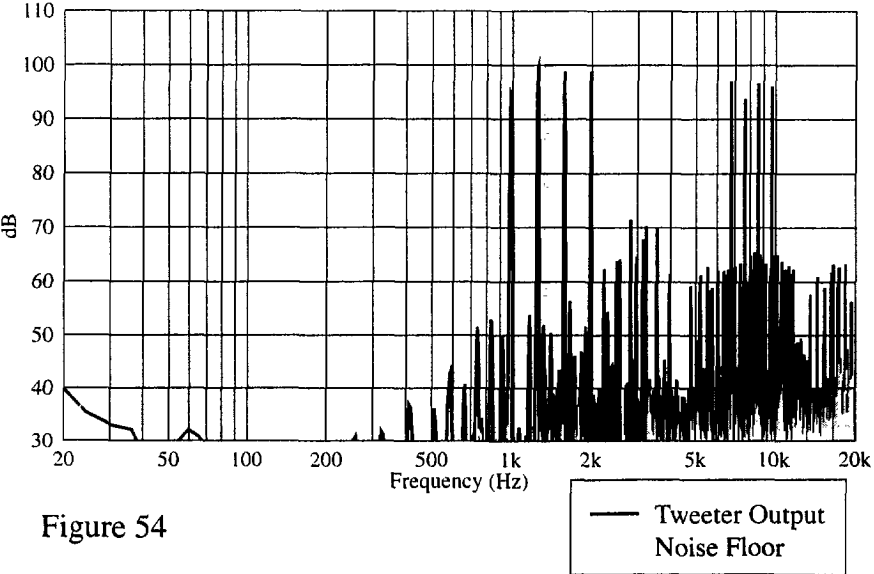
Woofer Tri-Band Spectral, 1W



Tweeter Phi12r Spectral, 1W



Tweeter Tri-Band Spectral, 1W



Split Band Spectral, Full Range Single Wire

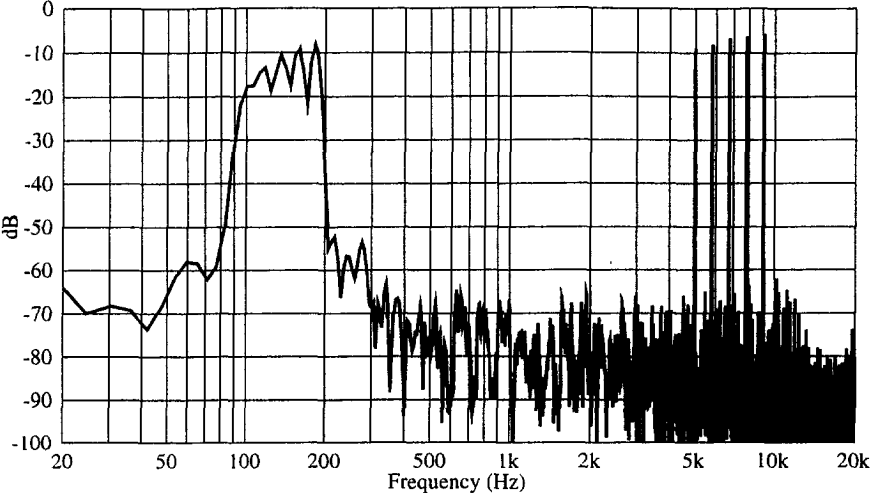


Figure 55

— Current Trans. Out

Split Band Spectral, Bi-Wire, Tweeter Cable

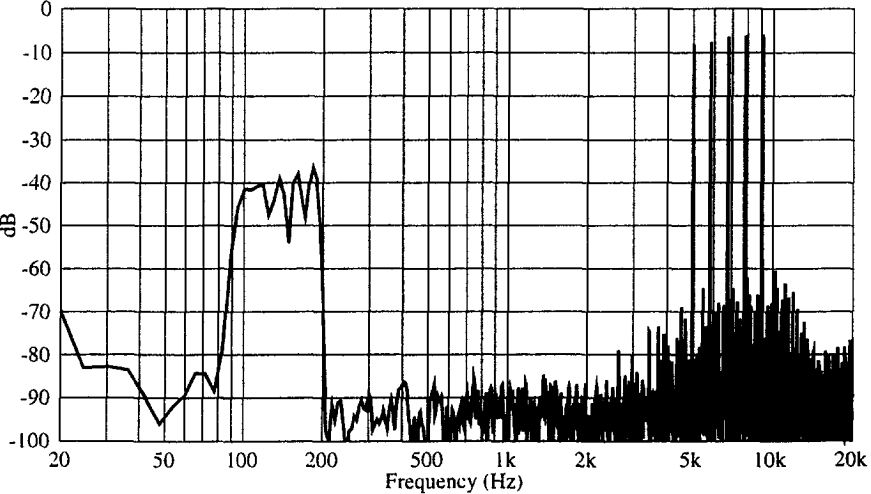


Figure 56

— Current Trans. Out

Split Band Spectral, Bi-Wire, Woofer Cable

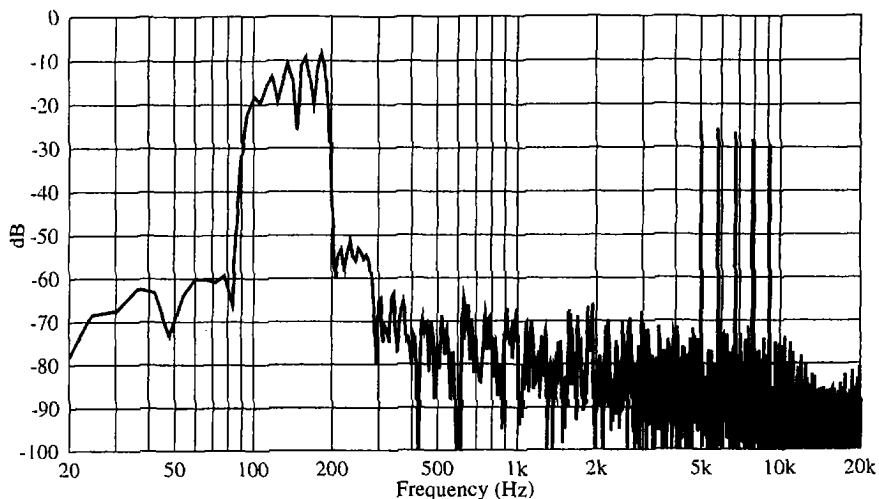


Figure 57

— Current Trans. Out

Split Band Spectral, Bi-Wire Vs. Single Cable

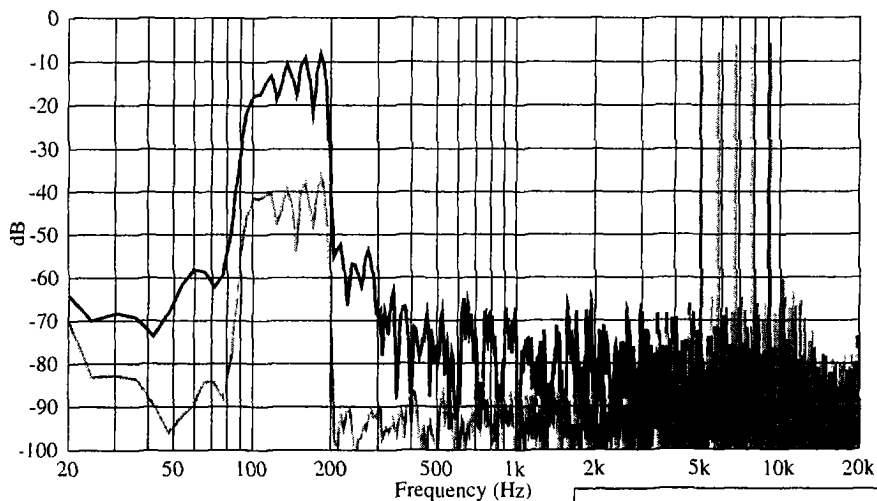


Figure 58

— Single Cable
— Tweeter Cable, Bi-wired