Errata

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HP References in this Application Note

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Harmonic Distortion Measurements

Application Note 378-1

Enhancing Speed and Performance with Spectrum Analysis

Introduction

Distortion measurements are among the most common of electrical measurements for an excellent reason: they reveal a great deal about the functioning and performance of a component, network, or system. In many applications, distortion measurements are one of only two or three measurement types necessary to define acceptable performance of a circuit or system.

The most flexible tool for distortion analysis is the spectrum analyzer. These analyzers are available in frequency ranges to cover the entire electrical spectrum and can measure many types of distortion including harmonic, intermodulation, spurious and sidebands. They can also provide many other measurements along with distortion and, thus, may make all or the majority of measurements necessary on a circuit or system.

The focus of this document is harmonic distortion. The most common and straightforward harmonic distortion measurements are those made on a single signal. But harmonic distortion is an equally important characteristic of networks and components such as filters and amplifiers. This document will cover both types of measurements. It will focus on practical measurement techniques and considerations, including those for particularly difficult or demanding measurements. It will help you make dependable, accurate distortion measurements with maximum speed and minimum difficulty.
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About Harmonic Distortion

Characteristics—Any periodic signal can be represented in the frequency domain by a combination of discrete sine and cosine signals of appropriate amplitudes and frequencies. A pure sinewave, for example, would be represented by a single discrete signal of the desired amplitude and frequency. Harmonic distortion is evidenced by unwanted energy at harmonics (integral multiples) of the fundamental or primary frequency. Harmonic distortion of the pure sinewave mentioned above could be represented by additional signals at multiples of the fundamental frequency.

For imperfect sinewaves, harmonic distortion is any change in the relative amplitudes of a signal's fundamental and harmonics. A good example would be music in a 2-port network, such as a filter or amplifier, where the signals involved are composed of multiple frequencies and are not purely sinusoidal.

Where harmonic distortion occurs, the bulk of the undesirable energy is usually concentrated in the first 2-3 harmonics, at two to four times the fundamental frequency. However, dozens of harmonics may be present on badly distorted signals, and significant harmonic energy may be present at frequencies far higher than the fundamental.

Causes—Harmonic distortion is caused by nonlinearities in the transfer function of a circuit, component or system. An example of a gradual nonlinearity is shown graphically in figure 1, where a transfer function is expressed as a plot of output vs. input. In practical systems, gradual nonlinearities are often the result of gain compression, transistor switching distortion or source-load impedance mismatches.

“Sharp” nonlinearities in transfer functions are also found in practical signals and systems. These highly nonlinear transfer functions (where harmonic distortion is greater than approximately 3%) are usually the result of transistor clipping or nonlinear circuit elements such as diodes. Distortion from these nonlinearities is measured in the same way as that from more linear circuits, though it behaves differently in response to signal level and other factors.

Why Measure Harmonic Distortion?

Distortion may be important in a circuit or system because the distortion itself is undesirable. In a communication system, for example, harmonic distortion can create energy at frequencies where none previously existed, interfering with other frequencies or channels.

Harmonic distortion can also evaluate proper operation or performance of a device. In an amplifier, for example, excessive harmonic distortion can indicate clipping, gain compression, switching distortion, improper transistor biasing or matching, or the effects of impedance mismatches. A harmonic distortion measurement, then, is often very effective as an overall performance indicator, verifying the proper combination of many factors.
Choosing a Measurement Tool

Since distortion is rarely the only measurement made on a circuit or system, other measurement requirements in an application will play an important role in the choice of an analysis tool. As an example, spectrum analyzers (using FFT or swept techniques) are often chosen for distortion measurements because of their ability to make other essential measurements such as frequency, signal level, amplitude linearity, frequency response, intermodulation distortion, etc.

Frequency Range— For most systems and signals, the harmonics of interest are limited to the first 3-10, since most sources and the circuits they drive are inherently band-limited to some degree. Thus, the frequency range of the analyzer should cover 3-10 times the fundamental frequency except where higher-order harmonics are expected or are a particular concern.

Swept or FFT Analyzer?— Though swept heterodyne analyzers are the principal subject of this document, other types of spectrum analyzers should also be considered. The most important alternative is the FFT analyzer or “dynamic signal analyzer.” These analyzers digitize a signal and perform a fast Fourier transform (FFT) to produce a spectrum display of amplitude vs. frequency.

FFT analyzers are generally restricted to harmonic distortion measurements on fundamentals of 30 kHz and below. They can measure frequencies as low as 1 mHz or less, and make harmonic distortion measurements 2-20 times faster than equivalent swept analyzers. With the ability to measure harmonic distortion of better than 0.01% (-80 dB), these analyzers are an excellent choice for the majority of low frequency measurements.
Measurement Procedure—Signals

Measuring harmonic distortion is conceptually very simple: identify and measure the fundamental signal and its principal harmonics. The material below describes basic measurements first. Then, a number of specific techniques are outlined for improving speed and performance, or handling more difficult measurements such as those involving excessive noise or extremely low distortion.

Input Configuration

An important first step is to terminate the signal to be measured in the appropriate impedance. This prevents impedance mismatches and the resulting signal reflections which can cause distortion and invalidate the measurement. It also prevents excessive loading of the circuit under test and the distortion that would result. The most common impedances for high frequency sources are 50 and 75 Ω, while many low frequency sources have low impedance outputs (often less than 1 Ω). For these low frequency sources, a “high” input impedance of 10k-1MΩ is typical.

Thus, reliable distortion measurements depend on proper input termination. The HP 3585B spectrum analyzer, for example, supplies 50, 75 and 1MΩ impedances to cover most measurement situations. Some other spectrum analyzers offer options for these impedances or accessory high impedance probes. Where signal power is low and the impedance mismatch is between 50 and 75 Ω circuits, resistive impedance converters may also be used. An example is the HP11852B 50Ω/75Ω minimum loss pad.

Input Range

Input range setting is a very important factor for overall measurement performance. As shown in the spectrum analyzer block diagram of figure 3, the input signal undergoes frequency translation by a mixer circuit before being measured. Spectrum analyzer inputs contain attenuators to provide an optimum signal level at the mixer. If the mixer input signal is too low, the measurement will have a high noise level, perhaps obscuring the harmonics to be measured. If the mixer signal is too high, the mixer will produce harmonic and intermodulation distortion of its own, thereby interfering with reliable measurements.
Fortunately, many modern spectrum analyzers, such as the HP 3585B, have autoranging functions to choose the best input mixer level. For most measurements, this circuitry provides an acceptable balance between noise and distortion.

In some cases, however, this setting can be further optimized specifically for harmonic distortion measurements. To do this, the drive level to the mixer is manually reduced so that its harmonic distortion approaches the extremely low noise levels obtainable by the use of narrow resolution bandwidths. This is an unusual situation, however, and is generally reserved for harmonic distortion measurements below -80 dBC (0.01%). For specific information on these measurements, see the following section on low distortion measurements and HP application note 246-1 “Optimizing the Dynamic Range of the HP 3585A Spectrum Analyzer.”

**Measurement Frequency**

The frequency range of the measurement should cover the fundamental frequency and its significant harmonics. Significant harmonics are generally those whose magnitude is within approximately 10 dB of the largest distortion product.

This is shown graphically in figure 4, where the contribution to total harmonic distortion (THD) of smaller distortion products is plotted. It can be seen, for example, that the THD of a signal is increased to 1.05 times its previous value with the addition of a 10 dB smaller harmonic. Thus, a signal with one harmonic at -40 dB (1.0% THD) would have essentially the same THD as one with an additional harmonic at -50 dB (1.05% THD).

Exceptions to this guideline should be made in applications where harmonics at certain specific frequencies are especially troublesome. Indeed, a very important advantage of a spectrum analyzer is its ability to separate and measure specific frequency components that are of special concern.

If the frequency bandwidth of the distortion products is known (for example, the output circuits of many signal sources are deliberately band-limited), the measurement frequency range can be set directly. This is accomplished with the Start/Stop Frequency or Center/Span Frequency keys and a numeric keypad or Up/Down step keys. The start frequency should be set lower in frequency than the fundamental signal by at least three times the resolution bandwidth to be used in the measurement (see the information below on choosing a resolution bandwidth). The stop frequency should be similarly higher in frequency than the highest harmonic to be measured.

Another major advantage of the spectrum analyzer as a distortion measurement tool is its ability to make reliable measurements of signals where the distortion characteristics (magnitude and frequencies) are unknown. In these situations, the start frequency should be set to 0 Hz (or the lowest frequency covered by the analyzer) and the stop frequency should be set to 20 times the fundamental frequency. In virtually all practical systems, this will ensure no
significant harmonics are missed. The stop frequency can then be progressively reduced after each sweep until an appropriate frequency span is determined. During this procedure, many spectrum analyzers will automatically adjust parameters, such as resolution bandwidth and sweep time, to maintain a useful and calibrated measurement display as stop frequency (or span) is reduced.

Reading the Result

Making the actual measurement is now just a matter of reading the relative amplitude of the harmonics from the measurement trace on screen. Reading the amplitude of the fundamental and comparing it with the individual harmonics is done most easily with the marker and a relative marker amplitude function. The following paragraphs describe this procedure as it applies to the HP 3585B spectrum analyzer.

Begin by measuring the fundamental signal, usually the strongest signal in the displayed frequency span. Move the marker to it by pressing the HP 3585B PEAK SEARCH key. Because harmonic distortion measurements are a comparison of the amplitude of the harmonics to that of the fundamental, a relative measurement is made with the fundamental as an amplitude reference. Turn on the offset (or relative) function by pressing the OFFSET key.

Then select a reference point corresponding to the current marker values by pressing the ENTER OFFSET key. Now the marker readout will show an offset of 0 Hz and 0 dB.

To measure the individual harmonics, move the marker sequentially to each one. This is easily accomplished on the HP 3585B by successive presses of the NEXT PEAK or NEXT R (Next Right) keys. If no other signals are present in the measurement, both of these functions will work equally well. The marker amplitude value will indicate the level of each individual harmonic distortion product, while the marker frequency values will be integral multiples of the fundamental frequency.

In many applications, the interest is not in individual harmonics, but in an overall figure-of-merit such as total harmonic distortion. To obtain a THD value, the distortion contributed by the significant harmonics is summed using the formula below.

\[
\text{THD} (%) = 100 \times \sqrt{\frac{(A_2)^2 + (A_3)^2 + \ldots + (A_n)^2}{A_1}}
\]

where \( A_1 \) = fundamental amplitude (volts)
where \( A_2 \) = second harmonic amplitude (volts)
where \( A_3 \) = third harmonic amplitude (volts)

This expresses the ratio of equivalent distortion power to fundamental power (in volts) as a percentage.

Since spectrum analyzers display signal amplitudes in logarithmic units and this formula uses linear voltage, the individual harmonic amplitudes must be converted. To avoid absolute voltage calculations, all terms are measured relative to the fundamental. As mentioned previously, note that harmonics which are at least 10 dB below the largest individual one do not contribute significantly to the overall measure of THD.
Improving the Measurement—Techniques for difficult applications and maximum performance

A) Lowering Noise Level and Improving Dynamic Range—For measurements where the harmonics are very small and obscured by noise, there are several options for reducing noise level. Since resolution bandwidth is the most important factor in determining overall noise level, this parameter should be considered first for modification. Narrower resolution bandwidths yield lower noise levels; in most analyzers, the overall noise level will decline approximately 10 dB for each tenfold reduction in the resolution bandwidth.

Narrowing video bandwidth can also lower the effective noise level slightly, but this improvement is usually limited to 2-5 dB. A change in video bandwidth acts to "smooth" (reduce the variance of) the noise level in a measurement trace, rather than to reduce noise level overall.

Narrower resolution and video bandwidths may require slower sweeps, however. Sweep rate (Hz/sec) varies with the square of the bandwidth, and thus a sweep with a 10 Hz resolution bandwidth may take 100 times as long as one with a 100 Hz bandwidth. Since the minimum sweep time of an audio/video/baseband analyzer such as the HP 3585B is 0.2 sec, this effect is most significant for measurements where the resolution bandwidth is smaller than approximately 100 Hz. For suggestions on improving efficiency where measurement speed is a problem, see the section below.

B) Improving Measurement Speed—Where the combination of frequency span and resolution bandwidth requires an unacceptably long sweep, or where additional measurement speed is otherwise desired, the following techniques can offer substantial speed improvements.

As noted above, measurements made with narrower bandwidths can take significantly longer than those made with wide bandwidths. One solution, then, is to increase resolution bandwidths wherever possible. In the absence of interfering signals, resolution bandwidth need be no narrower than that which is necessary to separate and measure the individual harmonics. In some cases, this can be up to 10 times wider than the default selection of the analyzer (since the default parameter selections of spectrum analyzers are designed to separate more closely spaced signals as well). See figure 6. Where a wider resolution bandwidth would not be selective enough, would not provide a sufficiently low noise level, or would not provide the necessary speed improvement, the best way to speed up a measurement is to stop sweeping. Some analyzers with fully synthesized local oscillators can be directly tuned to the harmonics of interest, eliminating the time necessary to measure all intermediate frequencies. This is
particularly true of applications where the analyzer is under computer control. In this mode, the analyzer is performing as a tuned receiver or selective level meter.

This direct tuning procedure for the HP 3585B is as follows: Begin with an on-screen display which includes the fundamental signal. Choose a resolution bandwidth which provides the required frequency selectivity and noise level (see above). Then press the **PEAK SEARCH** key to position the marker on the fundamental signal. Press the **COUNTER** key to obtain a precise measurement of the fundamental frequency, followed by the **MANUAL** key in the **Sweep** key group. This stops the sweep and selects CW (fixed frequency) analysis at the marker frequency. Then press the blue shift key and the **OFF-SWAP** key to execute the shifted function **MARK OFF-STEP**. This enters the precise fundamental frequency as the step size for successive measurements.

**Turn on the relative marker function and select the current marker position as the reference.** To measure the harmonics individually, simply press the **CENTER FREQUENCY** key followed by the **4STEP** key. Each successive press of the **4STEP** key will then provide a measurement of the next harmonic, with the relative amplitude of the signal displayed as the marker value.

**C) Improving Measurement Accuracy**—The accuracy for most distortion measurements using the HP 3585B and the swept techniques described above is approximately ±1 dB (typical) for each harmonic. While this is sufficient for many applications, it can be improved to ±0.25 dB (typical) per harmonic by eliminating frequency response and amplitude linearity error terms. The manual tuning procedure described above and the **MKR-REF LV** key make this an easy task.

Measurements should be made with the technique described immediately above. When each harmonic is individually measured, the reference level should be set at the level of the harmonic to be measured (the **MKR-REF LV** key will be helpful in accomplishing this). This ensures that each measurement is made at the reference level, while the use of the CW measurement technique ensures that each measurement is made at the "manual" frequency. Thus, the errors due to frequency response and linearity errors are avoided.
D) Optimizing Input Range for Low Distortion Measurements—
For measurements where harmonic distortion performance is the primary consideration, an analyzer's automatic range selection may be improved by reducing the signal level at the input mixer. This is accomplished simply by selecting a higher input range.

For example, the autoranging algorithm of the HP 3585B ensures that analyzer generated distortion products are more than 80 dB below the input range while also minimizing the analyzer's noise level. Selecting a higher input range will reduce the analyzer's internal distortion products substantially, but may cause an increase in relative noise level. If necessary, this increased noise level can then be countered by making the measurement with a narrower resolution bandwidth.

The optimum input range for harmonic distortion measurements is usually 5-10 dB above the range automatically chosen by the analyzer. With this technique, the effective internal harmonic distortion of the analyzer can typically be reduced by 5-10 dB. In the HP 3585B, for example, this often permits measurement of signals whose harmonics are as low as −100 dB!

E) Improving Noisy Measurements—In measurements where noise from the analyzer or from the signal under test is not at least 10 dB below the harmonic being measured, the amplitude reading will be somewhat unstable. The best remedy is usually to reduce resolution bandwidth, thereby reducing noise in the measurement bandwidth. If resolution bandwidth coupling remains enabled, this will also result in a narrower video bandwidth, further improving measurement stability.

As an alternative or for additional improvements, the video bandwidth can be further reduced. The most effective video filtering requires a video bandwidth of 1 to 10% of the resolution bandwidth. However, sweep time will be automatically increased and may become unacceptably long. If this occurs, see the techniques described in the preceding section on improving measurement speed.

F) Limit Testing for Automatic Pass/Fail Results—Analyzers which incorporate automatic limit testing features can speed analysis and provide faster go/no-go decisions. The automatic limit testing feature of the HP 3585B, for example, is useful where it is necessary to verify that no individual harmonic exceeds a user-defined level. Entered limits are checked at the conclusion of
Measurement Procedure—Networks

Introduction

Measurement of harmonic distortion on networks and systems (such as filters and amplifiers) is very similar to distortion measurements on signals. The principal difference is that a suitable stimulus signal must also be supplied in the measurement process.

Stimulus Signal Requirements

Signal Level—In most circuits (especially active ones), harmonic distortion varies as a dramatic function of operating signal level. Therefore, it is important to supply the network under test with a signal which approximates normal operating conditions.

Of course, the signal source must also have an appropriate output impedance to properly drive the network. Audio frequency measurements can usually be performed using sources with 50Ω outputs—the standard configuration for most electronic test equipment. Video applications, however, often require sources with 75Ω output impedances.

Harmonic Distortion—Where the harmonic distortion of the stimulus signal is 15-20 dB lower than that of the device under test, its distortion can usually be ignored. In applications where such performance is not readily available, there are several choices.

First, the stimulus signal can be filtered to improve its harmonic distortion. Low-pass or band-pass filtering will reduce unwanted harmonics and may also reduce broadband noise level, further improving the measurement. Filters can be constructed from passive or active components, and some commercial versions are available. In general, the lowest distortion is available from single-frequency passive band-pass filters.

In situations where the harmonic distortion of the signal source is only slightly lower than that expected from the network under test, additional measurements are suggested. The signal source itself should be measured, and these measurements compared with the test network. Where the most significant harmonics of the network under test are not more than approximately 15-20 dB greater than those of the signal source, results will be questionable. In this situation, measurement accuracy can not be improved without some improvement in the harmonic distortion of the signal source.

With these considerations in mind, harmonic distortion measurements on components or networks are little different from those on signals as previously described. All of the suggested techniques for improving distortion measurements will apply.
Combining Measurements for Productivity

Spectrum analyzers are generally more complex and expensive than dedicated distortion analyzers. Since this expense and complexity is justified by their additional measurement capability, these additional capabilities should be explored for most applications.

Modern spectrum analyzers can make fast, accurate measurements of power, frequency, non-harmonic distortion, noise, flatness or frequency response, amplitude linearity and others. They are most productive when their capabilities are used to fully characterize signals or systems. For more information on practical electronic measurements with spectrum analyzers, see the other application notes in this series.

References

HP 3585B operating manual
Ordering Number: 03585-90004

Application Note 150
Spectrum Analyzer Basics
Ordering Number: 5954-9130

Application Note 150-11
Spectrum Analysis..
Distortion Measurement
Ordering Number: 5952-9235

Application Note 246-1
Optimizing the Dynamic Range of the HP 3585A Spectrum Analyzer
Ordering Number: 5952-8815

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