HEWLETT hp PACKARD

Spectrum Analyzer Series
Application Note 150-11

SPECTRUM ANALYSIS... Distortion Measurement

Introduction

Minimization of signal distortion has high priority in design and production. Distortion may be noted as deviation from desired performance, regardless of its origin. However, if distortion is present, it must be accurately characterized to be dealt with.

Distortion falls into two general areas: spurious and predictable. Spurious signals are unrelated to the carrier signals present. For example, parasitic oscillations may occur in an amplifier at a frequency unrelated to the input. Harmonic and intermodulation distortion are common, "predictable" problems which fall at frequencies directly related to the input signal frequencies. This note describes predictable distortion characteristics and how to distinguish them using a spectrum analyzer.

Input-Output Relationships

The transfer characteristics of our test devices may be realized using a Maclaurin series and appropriate coefficients. Generally,

$$E_o = A_o + A_1E_i + A_2E_i^2 + \ldots + A_nE_i^n$$

where E_0 is the output voltage
E_i is the input voltage
A_n terms are constants.

If the device is linear, only the A_0 (dc) and A_1 (fundamental) terms exist. Thus, for two input signals applied to a linear device, the output signals must be of the same frequency (amplitude and phase variations may occur).

However, since our devices (transistors, diodes, etc.) are non-linear, the situation is quite different. If E_i consists of two sinusoids $E_1 \cos 2\pi f_1 t$ and $E_2 \cos 2\pi f_2 t$ the output may contain:

Fundamentals:

$A_1E_1 \cos 2\pi f_1 t$

$A_1E_2 \cos 2\pi f_2 t$

Second Order Products:

$A_2E_1E_2 \cos 2\pi (f_1 \pm f_2) t$

$(1/2)\, A_2E_1^2 \cos 2\pi (2f_1) t$

$(1/2)\, A_2E_2^2 \cos 2\pi (2f_2) t$

Third Order Products:

$(3/4)\, A_3E_1^2E_2 \cos 2\pi (2f_1 \pm f_2) t$

$(3/4)\, A_3E_1E_2^2 \cos 2\pi (2f_2 \pm f_1) t$

Note the relationship between the input and output signals. The output fundamentals are directly proportional to the input signals; the second order products are proportional to the square of the input signals; and the third order products are proportional to the cube of the input signals. These relationships will be useful in understanding later discussions.

Distortion Analysis

Harmonic distortion is directly related to a fundamental frequency signal and its integer multiples, called harmonics. (See Figure 1.) It is a measure of the relative amplitudes of the harmonic and fundamental signals. Often, interest is not in each harmonic's individual effect, but the "Total Harmonic Distortion," or THD. This may be found as follows:

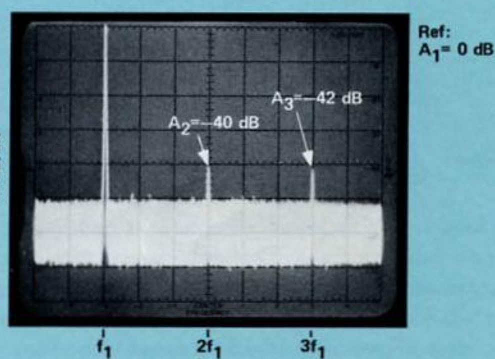
$$\text{THD } (\%) = 100 \times \frac{\sqrt{(A_2)^2 + (A_3)^2 + \ldots + (A_n)^2}}{A_1}$$

where A_1 = fundamental amplitude (volts)

where A_2 = second harmonic amplitude (volts)

where A_3 = third harmonic amplitude (volts), etc.

The spectrum analyzer, as used for this measurement, displays signals in logarithmic form (dB). All of the "A_n" terms are in linear voltage, and the log display of the analyzer must be converted for use. To do this easily and avoid absolute voltage calculations, all terms are measured relative to the fundamental. This sets A_1 to unity reference $(\log^{-1}(0/20) = 1)$. For example, if the second harmonic component is 40 dB below the fundamental, then A_2 (linear) $= \log^{-1}[-40/20]$, or $A_2 = 0.01$. If this is the only distortion present, our THD formula yields 1.0% total harmonic distortion.



In this example, second harmonic ($2f_1$) is 40 dB down from fundamental, and third harmonic ($3f_1$) is 42 dB down from fundamental. Using equation for THD and method mentioned:

$A_2 = \log^{-1}[-40/20] = .01$

$A_3 = \log^{-1}[-42/20] = .0079$

$$\text{THD} = 100 \times \frac{\sqrt{(.01)^2 + (.0079)^2}}{1}, \text{ or } 1.28\%$$

Figure 1. Harmonic Distortion.

Intermodulation Distortion is the interaction of two or more carrier signals and/or their harmonics creating additional frequency components at the output. The behavior of an intermodulation product is characteristic of its "order." The order is defined by the process generating each product. This is shown as follows:

$f_{out} = \pm n_1 f_1 \pm n_2 f_2 \pm \ldots \pm n_i f_i$,

where n_i = integer constants,

f_i = discrete fundamentals, and

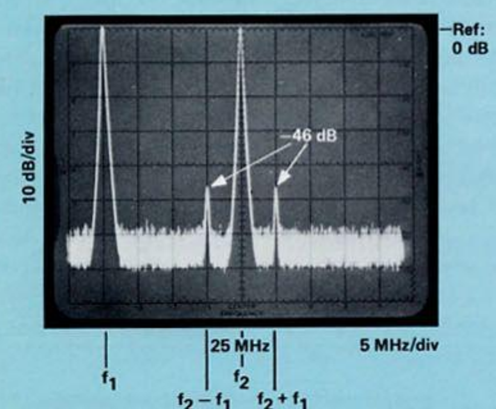
Σn = order of intermodulation product.

For example, a third order IM product may be comprised of a fundamental (f_1) and the second harmonic of another signal ($2f_2$), or three fundamentals (f_1, f_2, f_3).

$$f_{out} = 2f_2 \pm f_1 \text{ or } f_{out} = \pm f_1 \pm f_2 \pm f_3.$$

Of the many intermodulation products possible, second and third order problems are the most common.

Second order intermodulation is caused by two fundamental signals mixing to cause sidebands. The sidebands will be spaced about the higher frequency signal by the frequency of the low frequency signal. For fundamentals (f_1, f_2) at 5 and 25 MHz, the sidebands will fall at 20 MHz ($f_2 - f_1$) and 30 MHz ($f_2 + f_1$) for the difference and sum terms, respectively. This form of distortion is noticed most often in broadband systems. (See Figure 2.)

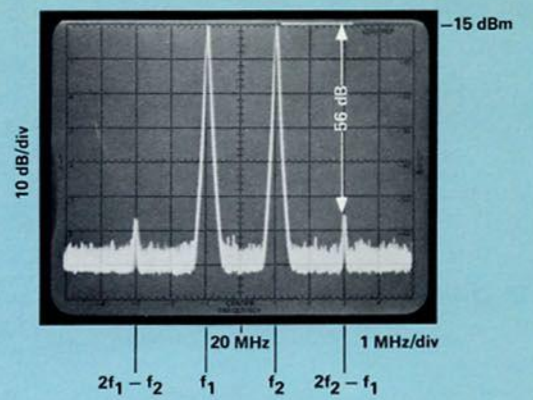


In this second order IM case, the distortion products are noted to be 46 dB below the carriers.

Figure 2. Second Order Intermodulation Distortion.

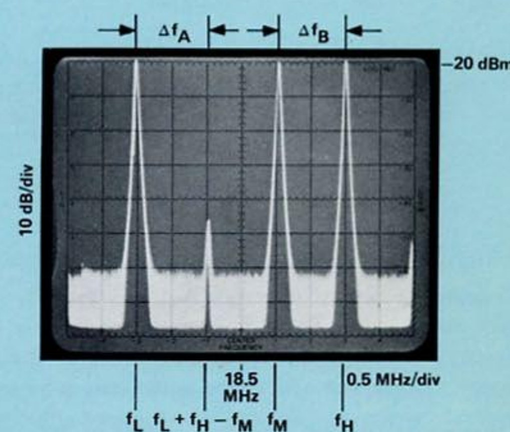
Third order intermodulation is a common problem in narrow band systems. There are two causes of third order IM, although they are seldom seen in the same system. The predominant case is when two signals are present, and strong second harmonic components are generated. The two signals (f_1 and f_2) mix with each other's second harmonic ($2f_1$ and $2f_2$) creating distortion products evenly spaced about the fundamentals ($2f_1 - f_2$ and $2f_2 - f_1$). The result is known as *"Two-Tone Third Order IM."* (See Figure 3.)

Triple beat is the other case, occurring when three fundamentals (f_L, f_M, f_H) mix to create multiple distortion products. This is seen in CATV systems where high level, closely spaced signals are present. Although identification of triple beat products is difficult, one product ($f_L + f_H - f_M$) always falls in band. This in-band product has an interesting characteristic: it and the three carriers have symmetric frequency spacing. (See Figure 4.) To show this, assume carriers at 16, 18, and 19 MHz. The in-band product is at 16+19−18 = 17 MHz. This yields Δf_A = 17−16 = 1 MHz and Δf_B = 19−18 = 1 MHz. The position of this product is then simple to locate.



Third order IM (two-tone) example shows distortion product suppression to be 56 dB below carrier tones.

Figure 3. Two-Tone Third-Order IM.



This triple beat example shows the in-band distortion product to be suppressed 46 dB below the carrier tones. Note the symmetry $\Delta f_A = \Delta f_B$. This symmetric pattern will always exist for triple beat distortion's in-band term.

Figure 4. "Triple Beat" Intermodulation.

Intercept Points

Thus far we have specified intermodulation distortion products by suppression, in dB, from the carriers. A problem here is that drive levels vary widely for different tests and devices, making the figures difficult to compare. An accepted method to normalize these differences is to define *"intercept points."* Intercept points are the theoretical points at which the fundamentals and intermodulation products have equal amplitude. "Theoretical," because gain compression eventually limits the output power to less than the intercept point. Intercept calculation is only valid when extrapolated from the linear operation range of the device under test.

To determine intercept points, some information is necessary:

1. Order of distortion product . . .
2. Device drive level in dBm . . .
3. Distortion product suppression at that drive level . . .

The order of the IM product is needed to determine its change in power for a change in the fundamental's power level. Intermodulation products are found to have a slope equal to their order; that is, a third order IM product would have a 3:1 slope. Thus, a 1 dB reduction in the carrier levels results in a 3 dB drop in third order product power, a gain of 2 dB in *relative* suppression from the carrier. A plot of *relative* suppression for an Nth order intermodulation product, then, would have a slope of (N−1):1. The equation below allows Nth order intercept calculation from this information.

$$I_n\,(\text{dBm}) = \frac{S}{N-1} + P.$$

where I_n is the Nth order intercept point in dBm,
S is the relative suppression from carriers in dB,
N is the order of the intermodulation product, and
P is the power level of the carrier tones, in dBm.

As an example, consider Figure 3 with two −15 dBm tones and 56 dB suppression of third order IM products. The Third Order Intercept (TOI) would be (56/2)−15 = +13 dBm.

If the intercept point is known, then the relative suppression of distortion products can be easily determined.

A nomograph has been provided to allow simple correlation of intercept point, tone level and intermodulation product suppression. (See Figure 5.) The blue example line is for Figure 3 measurement data.

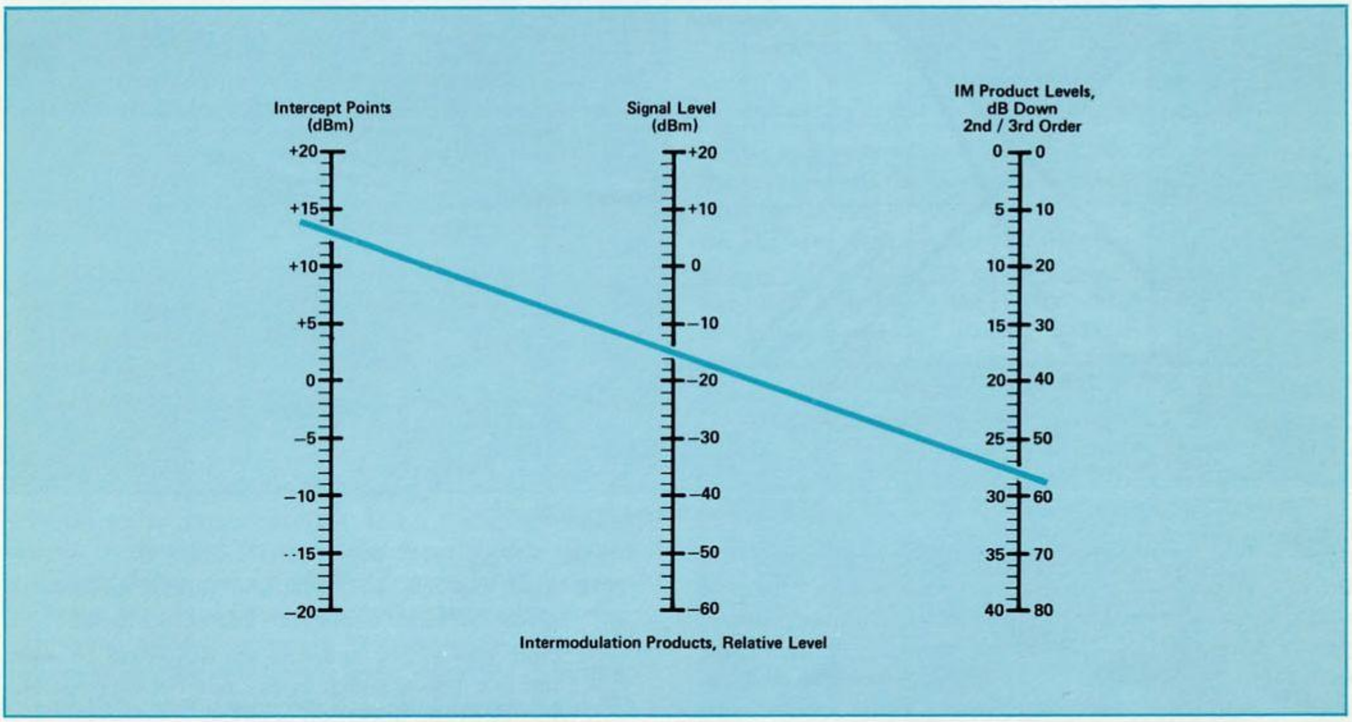


Figure 5. Intercept Point Nomograph.

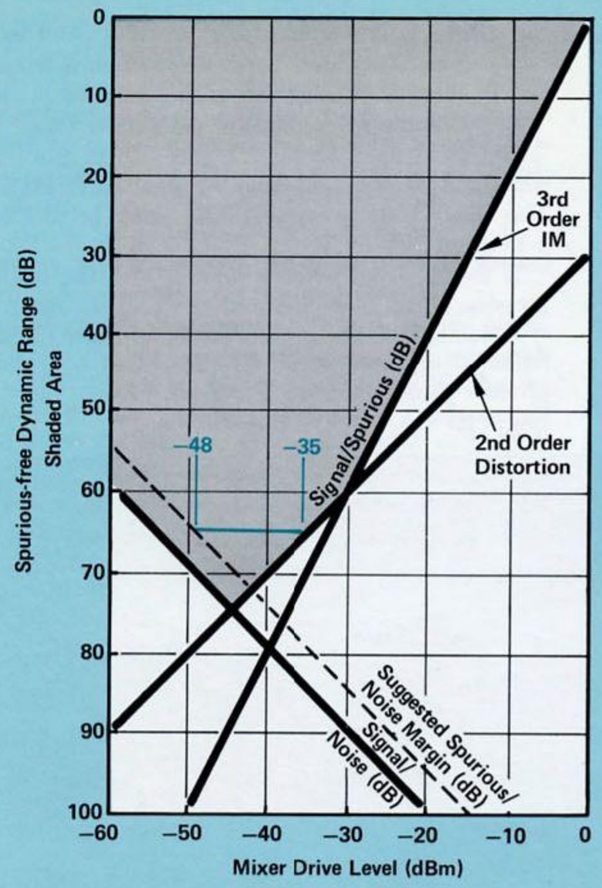
Measurement Accuracy

Measurement techniques are important when using a spectrum analyzer. Although many techniques may be used, this guideline helps provide consistent, accurate measurements. Both frequency and amplitude accuracy are necessary for signal characterization. For a complete discussion on spectrum analyzer accuracy, refer to Hewlett-Packard Application Note 150-8, "Spectrum Analysis . . . Accuracy Improvement."

Frequency accuracy is necessary to identify, by relative frequency spacing, the distortion products. The prime consideration is frequency span accuracy, found from the data sheet. This specification places a tolerance on the measured frequency separation, which helps in identifying the source of an intermodulation product.

Amplitude measurement requires wide dynamic range and spurious-free analyzer response. The power incident upon the analyzer's input mixer is a critical factor. In addition, small signals should be as high above the noise level as possible. This is due to analyzer detection methods. The signal and noise present are added after log shaping, resulting in a false (high) power displayed for signals near the noise level. Providing a 5 dB spurious-to-noise margin in dynamic range reduces the error to less than 0.4 dB, approaching zero for signals at least 8 dB above noise.

Achieving optimum dynamic range involves trade-offs between input signal levels and analyzer distortion. The data sheet contains information about noise level in each resolution bandwidth and distortion products generated by the analyzer vs. input level. A graph may be drawn from this information to determine dynamic range of the analyzer for various input levels. The noise level in the resolution bandwidth used is plotted as available signal-to-noise range (dB) vs. input level (dBm). The analyzer distortion suppression is plotted in a similar manner. For a given drive level, one of these limitations will determine



The graph at left was constructed from a Hewlett-Packard 8553B Spectrum Analyzer data sheet (1-110 MHz specifications), over a normal range of input power. The noise floor [mixer drive level (dBm)—S/N (dB)] is for a 1 kHz IF bandwidth. Generally, each decade reduction in IF bandwidth (B) reduces the noise floor (N) 10 dB, or $\Delta N = 10 \log B/B_0$.

As an example, assume 65 dB of spurious-free dynamic range is needed for a measurement. A quick glance at the graph notes drive level should be between −35 and −48 dBm at the mixer for the 1 kHz resolution bandwidth.

When measuring low level distortion, note that the spurious-free dynamic range defines the suppression of analyzer distortion. If the test device and analyzer distortion products are equal, the displayed distortion level may be up to 6 dB higher than actual. Thus, always allow a margin (5 dB or more) similar to the spurious-to-noise margin to avoid measuring the sum of analyzer and test device distortion.

Figure 6. Optimum Dynamic Range Chart.

the dynamic range of the analyzer. (See Figure 6.)

Having noted accuracy considerations, we may introduce a simple procedure to enhance our amplitude measurements. A technique known as IF substitution may be used to optimize analyzer accuracy. The technique involves:

1. Note test device signal levels and distortion specifications. Select RF attenuation to provide needed dynamic range, drive level.
2. Obtain desired display using resolution bandwidth, scanwidth, video filtering, etc.
3. Use the LOG REFERENCE LEVEL and vernier controls to place the distortion products at a convenient reference level.
4. Then use reference level and vernier controls to place the fundamentals at this reference line.

   Note this setting and find the difference between the two levels, which is the relative suppression, in dB, of the distortion product.

This technique may provide up to 3.5 dB improvement in measurement accuracy over random use of the analyzer's controls. Repeatability, important in production measurements, is also improved.

Utilization of the accuracy considerations, dynamic range graph and IF substitution allows you to perform quick, accurate characterization of device distortion with a spectrum analyzer.

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