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Application Note #3

Transmitter Spectrum Analyzer Test

How to measure amplifier non-linearity

How can the ham make practical amplifier measurements to check for splatter, IMD products and unwanted harmonic content? While it is helpful to understand the theory and math behind amplifier non-linearity's, all that is required is to make accurate measurements minimizing splatter and distortion is an understanding of the basic concepts.

Basically there are three methods to measure non-linearity and IMD products; Spectrum analyzer, Trapezoid test and the Two Tone test. Each has its advantages and disadvantages.

RF spectrum analyzer

The spectrum analyzer method is used to make quantifiable laboratory grade measurements. The spectrum analyzer test measures the amplifier's RF spectra distribution as a function of frequency, generally in MHz (X axis) and magnitude (Y axis). By comparing the level of the fundamental frequency to the level of any unwanted harmonic products (spurious) a precise quantifiable results can be obtained. The results are generally shown in the amount that the spurious products are down compared to the fundamental frequency and are express in dB. For example if the ratio is -20 dB than the spurious power is 1/100 that of the fundamental, and if the level was down -30 dB than the spurious power would be 1/1000 that of the fundamental. It should be noted that the spurious signals could be multiples of odd and even harmonics.

For convenience, some spectrum analyzer are equipped with a tracking generator. The tracking generator, by sweeping the amplifier's frequency, allows for measuring the performance at more than one frequency.

The frequency range of the spectrum analyzer should be at least five times the highest fundamental frequency to be measured. In the case of a 50MHz signal (6 meter) test, that would require a spectrum analyzer with a 250MHz frequency range or higher.

An alternative to the spectrum analyzer is using an oscilloscope that provides a Fast Fourier Transform (FFT) display. The FFT display is derived from the mathematical transformation of the signal's magnitude versus time components and then displayed as magnitude versus frequency. However, the oscilloscope's bandwidth needs to also be at least five times the fundamental frequency.

Either of these methods yields predictable and accurate measurement results. When comparing spectrum analyzer results to oscilloscope FFT results, and so long that the signal being measured is with the dynamic and frequency range of the measurement instrument input, the results are generally within .5dB.

Measurement considerations

While it is relatively straight forward to make these measurements, you need to consider the transceiver and or amplifier signal levels and the modulation being applied to their input. One can't simply just connect the high power RF output from the amplifier or transceiver directly to the input of the spectrum analyzer. This may result in damage to the instrument and may even cause injury to people. The power levels of even QRP transceivers are about 5 Watts and for transceivers can be as high as 200 Watts. Linear amplifiers can have levels of greater than 1,500 Watts. The levels are way out of the input range of a typical spectrum analyzer or oscilloscope. One could use attenuators. These would have to be wideband and high power. That means lots of money. The most economical way to condition the desired signal level is to use an RF sampler/coupler (see Figure 2).

While it is possible to just modulate the transmitter by speaking or whistling in to the microphone and observe the results, it is not recommended. Nonetheless, if such technique is used, it has been found that repeatable speaking the letter "X" will give the best results. The "ae" sound produces medium frequency levels for a long enough duration, and the "ks" sound produces higher frequency components to make some useful measurements. However, to make repeatable quantifiable measurements, a precision signal source, such as in Fig 3. below, a Two Tone test generator, is required.

Figure 1 3GHz spectrum analyzer

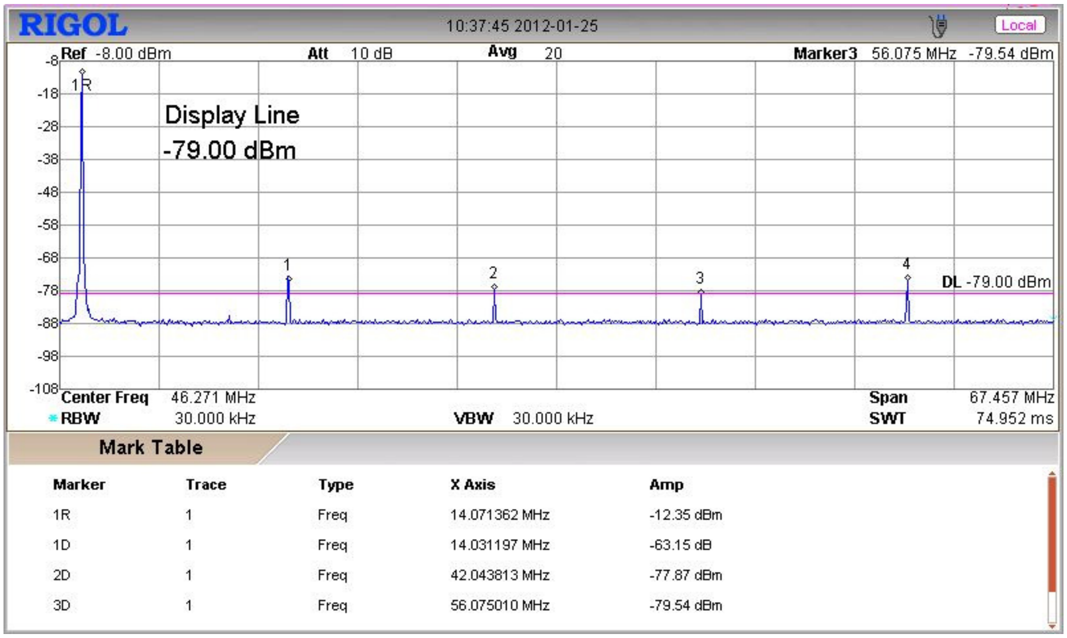
Fig. 1 The DSA1030A series spectrum analyzer with advanced measurement capabilities. It uses digital IF technology which guarantees the reliability and performance required meeting the most demanding RF applications for measuring amplifier no-linearity. This spectrum analyzer will make virtually all ham radio measurements and test. Price is about $5,000

Figure 2 HFS-1.5 HF sampler/coupler -30dB

Fig. 2 This wideband RF sample/coupler inductively couples a sample of high power RF (up to 1.5 KW PEP) passing from the RF IN to the RF OUT connector. This signal is coupled at -30 dB, a power reduction of 1000:1. The sampled signal is very useful for analyzing HF signals on an oscilloscope and spectrum analyzer.

Figure 3 TTG1 Two tone test generator

Fig . 3 The TTG1 Two Tone test generator is an excellent oscillator to test SSB transmitter performance such as Inter-modulation Distortion (IMD). The TTG1 was created to deliver a standard 2-tone (700 and 1900 Hz) audio source for testing of SSB transceivers and linear amplifiers. This type of testing is used as a measure of transmitter linearity for amateur radio transmitters.



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Ref -8.00 dBm Att 10 dB Avg 20 Marker3 56.075 MHz -79.54 dBm

Display Line
-79.00 dBm

DL -79.00 dBm

Center Freq 46.271 MHz Span 67.457 MHz

RBW 30.000 kHz VBW 30.000 kHz SWT 74.952 ms

Mark Table

Marker	Trace	Type	X Axis	Amp
1R	1	Freq	14.071362 MHz	-12.35 dBm
1D	1	Freq	14.031197 MHz	-63.15 dB
2D	1	Freq	42.043813 MHz	-77.87 dBm
3D	1	Freq	56.075010 MHz	-79.54 dBm

Figure 4 Spectrum analyzer display

Fig. 4 This example is a typical spectrum analyzer display. The fundamental frequency is the large spike at the start of the sweep. The harmonic contents are the smaller spikes. They are down from the fundamental frequency about 70 dB. The FCC minimum levels for the amateur radio service for unwanted IMD products is around -20dB. So in the example in Fig.4, this level would be considered excellent performance.

Summery

Using a spectrum analyzer or an oscilloscope with an FFT for amplifier distortion measurements provides the most accurate and repeatable results. However, there are always tradeoffs, see Fig. 5 below.

Test Equipment	Spectrum analyzer, RF Sampler/coupler, dummy load, signal source such as a two tone test generator.
Advantage	Results are displayed in quantifiable units, easy to duplicate, accurate to a dB or less.
Disadvantage	New laboratory grade spectrum analyzers are expensive.

Figure 5 advantages and disadvantages

Careful shopping on eBay will reveal that affordable used spectrum analyzers are available. It is recommended if such purchase is contemplated that it is calibrated with NIST certified equipment.

HF amplifier distortion measurements

Linear RF Power Amplifiers are used in a wide variety of ham radio stations. The output power of these linear amplifiers can range from a few watts to several thousand watts. FCC regulations limit the maximum power to 1,500 peak envelope power (PEP). When adjusted properly and operating in their linear region, these amplifiers do exactly that, they amplify RF energy without adding any significant additional distortion products.

However, if overdriven or not properly tuned, the potential distortion products can cause severe problems such as unintelligible modulation. RF power being transmitted out of band, thus causing interference with other radio communications. The interfering signals are the result of harmonic and intermediation products – sometimes referred to as “splatter”.

Efficiency

Another byproduct of improper linear amplifier operation is inefficiency. Power that is not converted to a useful signal is dissipated as heat. Power Amplifiers that have low efficiency have high levels of heat dissipation, which could be a limiting factor in a particular design. This can have an adverse effect on the components, particularly the final output tubes or transistors.

Instability

Another undesirable amplifier phenomenon is instability. Instability in RF amplifiers may manifest itself as oscillation at almost any frequency, and may damage or destroy the amplifying device. This unwanted RF energy is called spurious oscillation.

These spurious oscillations can arise at specific or very wide ranging frequencies and over a particular bias, drive level, temperature or output load impedance.

Responsibility

In the amateur radio service, the control operator (i.e. ham) is responsible for ensuring that all emitted signals including RF linear power amplifiers are operated in accordance with those prescribed by their license privileges and do not exceed the maximum allowed distortion by the FCC.

Some practical theory

In practice and to ensure efficiency, many linear amplifiers operate as Class B. In Class B the conduction angle for the amplifying device (tube or transistor) is approximately 180°. Thus, the amplifying device conducts only half of the time, either on positive or negative half cycle of the input signal.

The same as in Class A, the DC bias applied to the amplifying device determines the Class B operation. Class B amplifiers are more efficient than Class-A amplifiers. The instantaneous efficiency of a Class-B PA varies with the output voltage and for an ideal PA reaches π/4 (78.5 %) at PEP. However they are much less linear. Therefore a typical Class-B amplifier will produce quite a bit of harmonic distortion that must be filtered from the amplified signal.

$$PDC = (2*VCC*V) / (\Pi*R);$$

$$PLOAD = V2 / (2*R);$$

$$\eta \text{ (Efficiency Class-B)} = (\Pi*V) / (4*VCC)$$

A common configuration of Class B amplifiers is push-pull. In this configuration, one amplifying device conducts during positive half cycles of the input signal and the second transistor conducts during the negative half cycle. In this way, the entire input signal is reproduced at the output. In the push-pull arrangement, the DC components and even harmonics cancel, (but odd harmonics add), thus the output contains the fundamental signal only. Note that the cancellation of odd harmonics is only valid if the amplifier is not driven hard.

Power amplifier linearity

When two or more signals are input to an amplifier simultaneously, the second, third, and higher-order intermodulation components (IM) are caused by the sum and difference products of each of the fundamental input signals and their associated harmonics. The rated PEP of a Power Amplifier is the maximum envelope power of a two-tone signal for which the amplifier intermodulation level is -30dBc. When two signals at frequencies f1 and f2 are input to any nonlinear amplifier, the following output components will result:

Fundamental: f1, f2

Second order: 2f1, 2f2, f1 + f2, f1 - f2

Third order: 3f1, 3f2, 2f1 ± f2, 2f2 ± f1,

Fourth order: 4f1, 4f2, 2f2 ± 2f1,

Fifth order: 5f1, 5f2, 3f1 ± 2f2, 3f2 ± 2f1, + Higher order terms

The odd order intermodulation products (2f1-f2, 2f2-f1, 3f1-2f2, 3f2-2f1, etc) are close to the two fundamental tone frequencies f1 and f2.

The nonlinearity of a Power Amplifier can be measured on the basis of the generated spectra (i.e with a spectrum analyzer) than on variations of the fundamental waveform (i.e. oscilloscope). The estimation of the amplitude change (in dB) of the intermodulation components (IM) versus fundamental level change, is equal to the order of nonlinearity.

For a one dB increase of fundamental level (f1 and f2), the level of IM2 will go up by 2dB, the level of IM3 will go up by 3dB, and so on. As a relation between the degree of nonlinearity (third, fifth, etc) and the frequency of the side tone (such as IM3, IM5, etc). It can be mentioned with the IM5 tones are not affected by third-degree nonlinearities, but IM3 tones are functions of both third- and fifth-degree (and higher) nonlinearities. That means at low signal amplitudes, where the fifth-order distortion products can be neglected, the amplitudes of the IM3 tones are proportional to the third power of the input amplitude (see below).

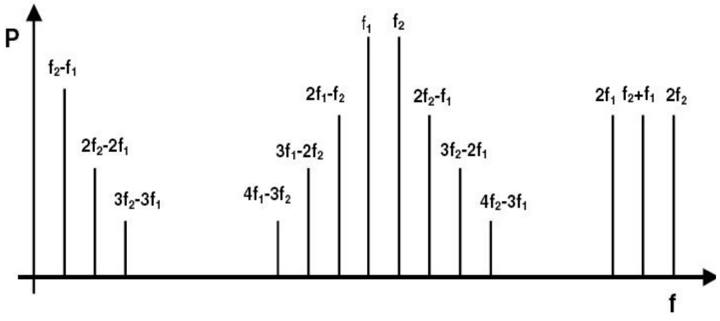

Figure 6 Spectrum of IMD products