Precision Two-tone RF Generator for IMD Measurements

Crystal oscillators plus crystal filters yield extremely low phase noise and high IP_3 IMD test generator for measuring the dynamic range of HF Receivers.

by Stuart Rumley, KI6QP

There have been numerous articles in amateur literature on the significance of high dynamic range performance in HF receivers.[1] Without sufficient dynamic range a receiver's other important virtues, mainly selectivity and sensitivity, soon become ineffective. Dynamic range can be specified and measured as either blocking dynamic range or intermodulation distortion (IMD) dynamic range. Blocking dynamic range refers to a receiver's ability to not be desensitized whenever strong signals are present. IMD dynamic range, on the other hand, refers to the receiver's ability to not generate false signals whenever there are two or more strong signal present. The IMD measurement leads directly to a convenient figure of merit for dynamic range known as the third order intercept or IP_3. The purpose of this article is to show how to construct an inexpensive source for making the IMD measurements, how to make the measurements and calculate IP_3, and compare some typical receivers.

In order to make the IMD measurements it is essential to have two, high stability, low phase noise RF signal source at the frequency of interest. The typical setup for measuring IMD usually looks something like figure 1[9]. Unfortunately most enthusiastic radio amateurs do not have one, let alone two, of the low phase noise synthesized signal generators such as the HP8640A shown. The two synthesizers are required because the two-tone IMD measurement requires two frequency stable sources set only a few kilohertz apart from each other.

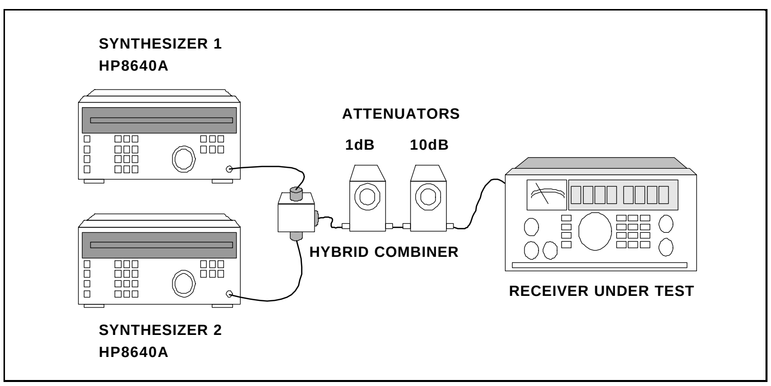


Figure 1--IMD measurement setup.

Attempting to make this measurement with unstable sources proves quite frustrating. If you are prepared to trade frequency agility for cost, two crystal oscillators operating at the desired test frequencies can prove to be just as useful and to some extent more convenient than a pair of synthesizers. Figure 2 shows a block diagram of the essential functions. There are two crystal oscillators, one for generating each tone.

Each crystal oscillator is followed by a crystal filter network tuned to the same frequency as the oscillator. The output of each crystal filter network is attenuated and then summed together in a hybrid combiner. The combined output from the hybrid is further filtered to remove harmonics. The frequency of 14.20MHz and 14.22MHz was selected as the optimum frequencies for the two crystal oscillators. This is approximately mid-range for most continuous coverage HF receivers (0.5 to 30MHz) and is also in the middle of the 20 Meter band so that it may be used with ham band only receivers as well.

The design of the two-tone IMD generator concept is rather simple, but a number of subtleties must be taken into consideration. In order to accurately measure receiver performance, the two tonw source must possess the following attributes.

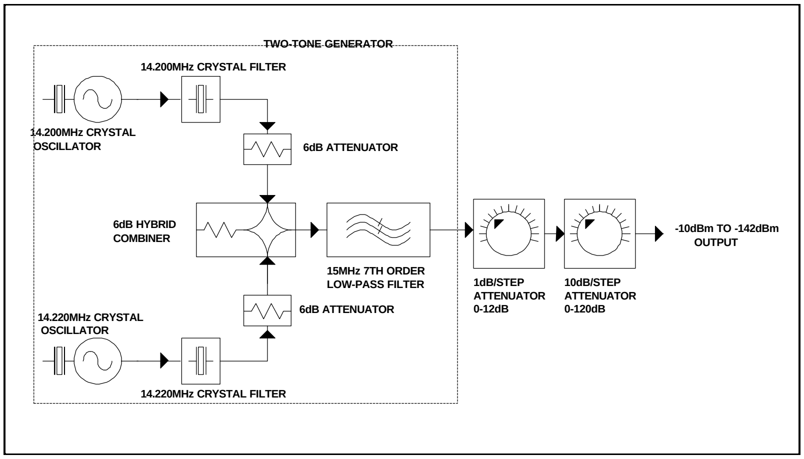


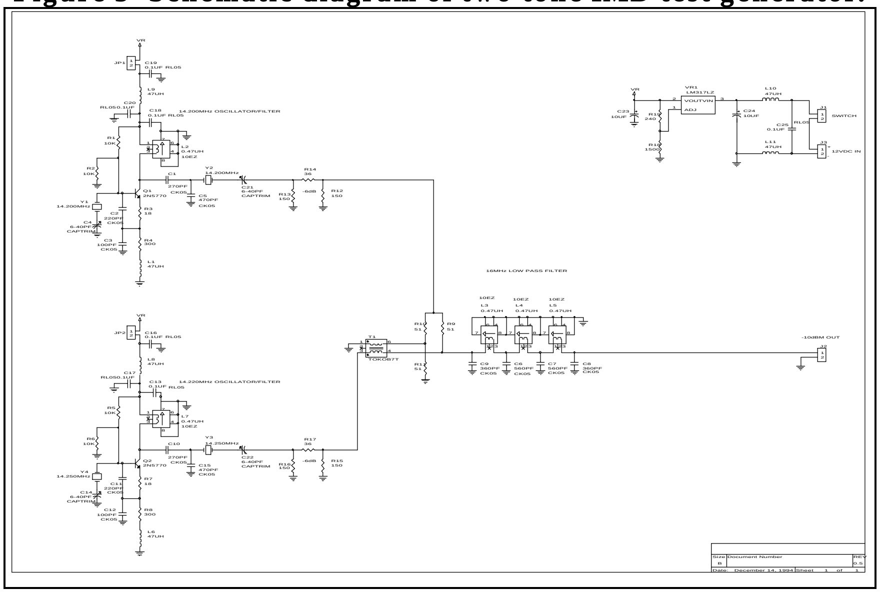
Figure 2--Block Diagram of Two-tone Source.

1. Low equivalent IMD to ensure that the distortion products measured are only from the receiver or system under test and not the test generator.
2. Low phase noise. The phase noise of both tones, at the frequency offset of the expected IMD products, must be much less than these IMD products.
3. Low harmonic energy. Because the third order IMD products do contain energy at the second and third harmonics of F1 and F2, it essential that the harmonic energy from the two-tone generator be extremely low so that the measurements will be accurate.
4. Careful filtering and shielding to ensure that external signals and noise do not interfere with the measurements.

Circuit Description

The detailed circuit schematic is shown in **figure 3**. Q1 and Q2 are fundamental mode colpitts crystal oscillators operating on 14.200MHz and 14.220MHz respectively. The selection of the actual frequencies is determined by two bounding requirements. One, the frequencies cannot be so close together that the test receivers cannot resolve the IMD products because of either selectivity limitations or phase noise from the receivers local oscillator. And two, the frequencies cannot be so far apart that the input band-pass filters will cause unequal attenuation of either tone. A good choice is 20KHz to 25KHz. The output from each oscillator is taken from the a tuned collector circuit in order to minimize harmonic energy and provide a low impedance source to the crystal filter network. The oscillators are operating at a rather high power level with over 10mA of collector current in each transistor. The high power is required in order to provide -10dBm at each tone to the output. This power level was selected so that at least 10dB of attenuation could be always be left in the step attenuators and still have adequate signal energy to create measurable IMD products in high dynamic range receivers. The reason it is desirable to leave some attenuation between the IMD generator and receiver under test is because the receiver cannot be trusted to provide a good 50Ω match to the IMD generators output filter. The 10dB attenuation guarantees at least 20dB return loss to both the IMD output filter and the receivers input band-pass filters system.

Figure 3--Schematic diagram of two-tone IMD test generator.



Crystal oscillators generally have quite low phase noise, but operation above 1mA. can degrade their performance to some degree. In order to maintain extremely low phase noise a couple of additional measures where taken. The emitter degeneration resistors, R3 and R7, provide negative feedback which reduces the oscillator phase noise. Following each oscillator is a narrow band crystal filter network C1,C5, Y2 and C10,C15, Y3. The crystal filters provide an additional 30dB of phase noise attenuation at a carrier offset of +/-10KHz. The addition of the crystal filters might seem a bit excessive but considered necessary and desirable in order to be absolutely sure that the phase noise performance of the two-tone generator did not preclude the ability to measure low level IMD products in high performance receivers. An additional benefit of having two very clean sources is the ability to evaluate the phase noise and reciprocal mixing in the receiver under test.

The outputs from each of the crystal filter networks are passed through 6dB attenuators comprised of R12,R13,R14 and R15,R16,R17 and then summed in the hybrid combiner network made up of T1, R9,R10 and R11. The attenuators are required in order to isolate the combiner from the crystal filters and to provide a consistent impedance for both. The combiner sums the two frequencies with an insertion loss of 6dB and approximately 40dB of isolation. This combination of filters, attenuators and combiner provide a great deal of isolation between the collectors circuits of the two oscillators (>90dB). Together with good physical isolation, this topology prevents the generation of any significant internal IMD products.

The output harmonic filter is a seven section all pole design based on the same inductors used for the oscillator. This filter adds approximately 1dB of insertion loss at the operating frequency and >50dB at the second harmonic and >70dB at the third harmonic. From the output of the crystal filter, the second harmonic is down >40dB and the third harmonic is down >55dB. The resulting output then is a second harmonic less than -100dBm and a third harmonic less than -135dBm. These levels are so low that they will not contribute in any measurable way the IMD values of the receiver under test. Because the second harmonic is less than -100dBm makes it practical to search for second order products at 28.400MHz, 28.420MHz and 28.440MHz.

Use good RF proto-typing techniques in constructing your unit, short lead lengths, good grounding and shielding. Be particularly careful to provide some physical separation between the oscillators, crystal filters, combiner and harmonic filter. If inadequate shielding or isolation is provided then IMD products will form in the oscillators from cross coupling. Similarly, isolation is required around the crystal and low pass filters in order to maintain there good cut-off characteristics.

Because there are a number of coils used in this project, no attempt was made to use hand wound toroid inductors. I think they would be too tedious to wind and lack the adjustability. The inductors used, however, are a quality product, inexpensive and readily available[12].

Alignment:

Alignment of the generator is straight forward, only an oscilloscope , frequency counter and a 50Ω feedthrough termination is required. The feedthrough termination is used in conjunction with the oscilloscope in order to provide the proper load impedance to the generator.

First each oscillator and filter combination is tuned up independently. Begin by disabling one of the oscillators by removing one of the supply jumpers at a time. Optimize the output of the other oscillator by adjusting the collector inductor L2 or L7 for maximum output on the oscilloscope. The oscillator that is running is then set on frequency with the frequency counter by adjusting the appropriate trimmer, either C4 or C14. After the oscillator is set on frequency, remove the counter and connect the oscilloscope again. Now carefully adjust the corresponding filter tuning trimmer, either C21 or C22 for maximum output. Repeat this process for the alternate oscillator and filter combination.

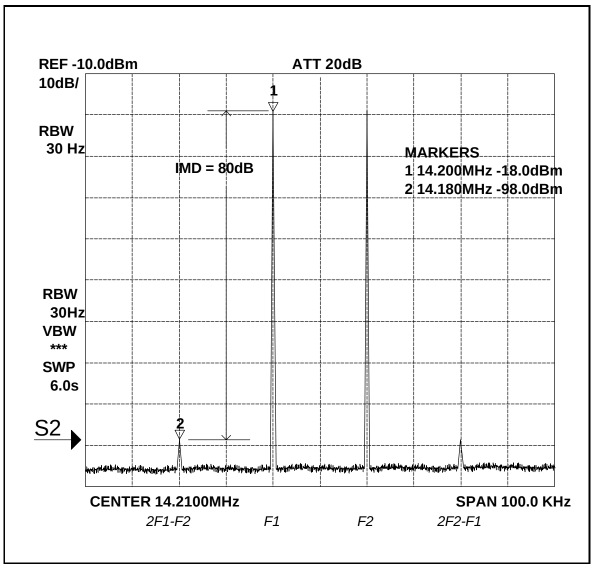


Figure 4--Typical 3rd-order IMD products as seen on a spectrum analyzer.

Adjustment of the output filter is not critical. Alternately adjust each inductor L3,L4 and L5 for maximum output from either oscillator. Adjustment by this method should give second harmonic attenuation values within a dB or so of what you might achieve using a network analyzer to set this filter.

Finally, with the oscilloscope and termination still connected (by the way, the termination should be at the 'scope end of the cable) alternately disable one of the oscillators at a time and again trim L2 or L7 for –10dBm output for each frequency. Minus 10dBm corresponds to 200mV Pk-Pk into 50Ω.

Intermodulation Distortion (IMD) Measurements

By definition any linear circuit element would produce zero IMD products (see appendix A). It is precisely this degree of non-linearity we wish to represent and measure by making IMD measurements. The most troublesome of the intermodulation products are the so called third order products. These are $2F1–F2$ and $2F2–F1$ signals shown on the hypothetical spectrum analyzer in **figure 4**. If you were attempting to copy a weak signal (with a receiver with similar IMD performance), at or near one of these intermods frequencies, you would suffer some interference. The higher your receiver's IP_3 value (in dBm), the lower these third order products and the consequential interference will be. Notice that the third order IMD product ($2F1$-$F2$) in **figure 4** is shown as 80dB below the two signals $F1$ and $F2$. If the power levels of $F1$ and $F2$ were to decrease by 10dB, the power levels of the third order IMD products would decrease by 30dB. Because the level of the third order IMD products are dependent on the input signal level as well as the non-linearities of the system, the third order intercept or IP_3 is a more useful figure of merit for system performance because it is independent of the signals' amplitude.

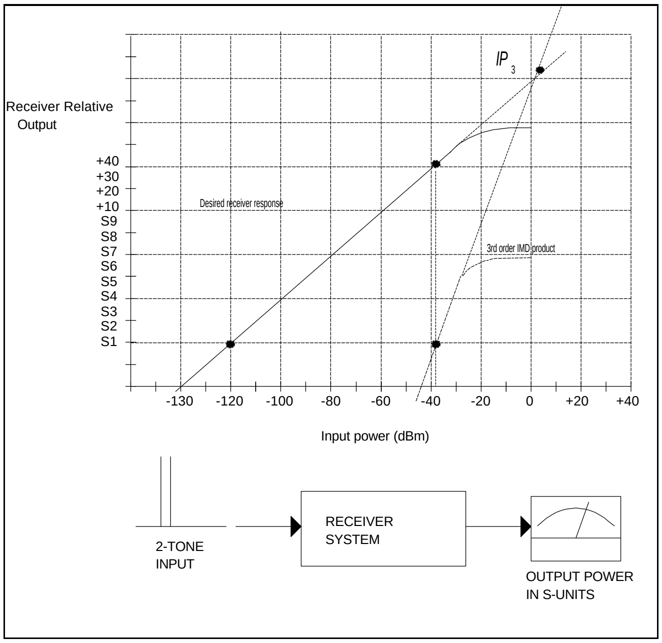


Figure 5--Third order intercept

Figure 5 is a graphical representation of the IP3 concept. As can be seen from the graph, if the intercept point is known, the level of the third order intermodulation product can be determined. In the example of figure 5, if two-tones at -38dBm where applied to this hypothetical receiver system, with an IP3 of +3dBm, their fundamental signal amplitudes would measure +40dB (over S9) and the third order intermodulation products would measure S1.

Making the Measurements:

To make the 3rd-order IMD measurements, connect the test receiver and attenuator set to the two-tone IMD source as shown in **figure 6**. If you don't already have a set of step attenuators you can build your own from designs in the ARRL Handbook. To get a feel for what to expect, begin by setting the attenuators for a combined value of 20dB. Now tune the test receiver from 14.175MHz to 14.245MHz, most receivers will have a noticeable 3rd-order intermod at 14.180MHz and 14.240MHz plus the two very strong fundamental signals at 14.200MHz and 14.220MHz. Your receiver should be set to either USB or LSB mode with the AGC on, RF attenuator to 0dB and any preamplifier off . You may argue that the AGC should be off when making the measurements so that the RF and IF amplifiers will be at maximum gain. I would agree, but the problem is the S-meter will probably not be working with the AGC off and it is required in order to make the necessary measurements.

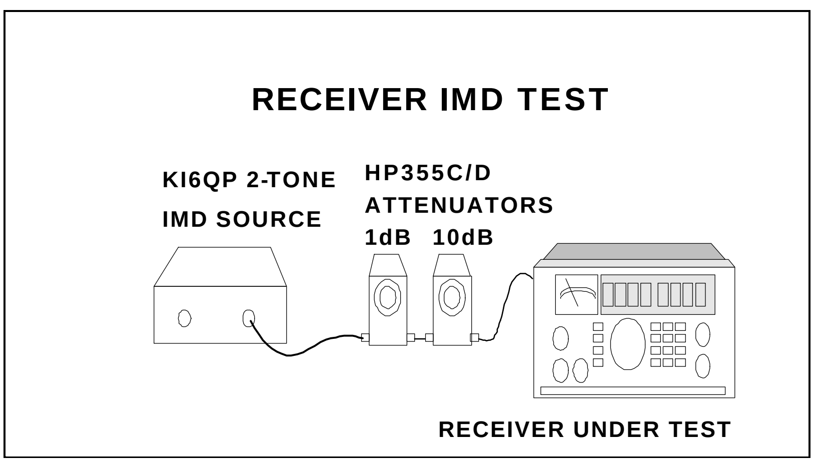


Figure 6--IMD measurement setup

Now that you have found the intermods, begin the measurement process by calibrating the receiver's S-meter. It is only necessary to calibrate the S-meter at one low level value, say S1 or S2. This is done by setting the attenuators to a combined value of approximately 100dB (-110dBm) and tuning the receiver to either 14.200MHz or 14.220MHz. Adjust the 1dB/step attenuator until the S-meter reads exactly S1 or S2. The choice of which to use depends on how responsive the meter is to a 1dB attenuation change; some receiver's meters will not respond well at S1 so try S2 instead. Try to avoid using anything higher than S2 because the AGC will begin to function and could start to affect the linearity of the receiver's input circuits. The idea is that you should be able to resolve a reference level within +/-1dB variations in input signal strength at some very low level near the receivers noise floor. Now, you should have an absolute signal level corresponding to a particular S-meter value. Record signal level (P_{IM}) as –10dBm minus the combined attenuator values.

Now, tune the receiver to either 14.180MHz or 14.240MHz and increase the signal level by decreasing the value of attenuation until the IMD signal is equal to the previously established S-meter calibration point. Record this signal(P_A) as –10dBm minus the combined attenuator values. The IMD at this particular signal level is the difference in attenuator values P_A–P_{IM}. The IP_3 is equal to P_A plus half of the IMD value. Sounds confusing, so let's do and example:

With the receiver tuned to 14.200MHz, let's say S2 required a combined (10dB/step and 1dB/step) attenuator settings of 88dB, therefore P_{IM} = –10dBm –88dB = –98dBm. And with receiver tuned to IMD frequency of 14.180MHz the combined attenuator settings where 18dB, therefore P_A = –10dBm –18dB = –28dBm. So, IP_3 =(–28dBm – –98dBm)/2 + (–28dBm)= +7dBm. This is derived from the more generalized form of intercept point: $IP_n = \frac{nP_A - P_{IM_n}}{n-1}$. Which in this particular example would look like: $IP_3 = \frac{3(-10dBm - 18dB) - (-10dBm - 88dB)}{3-1} = 7dBm$. You can use either method you prefer. I like the first example because I can do it in my head. As another example, consider the hypothetical spectrum analyzer shown in **figure 4** and see if you can determine its IP_3 in your head, -18dBm +80dB/2 =+22dBm.

Shown in **table 1** below is how a few familiar receivers compared in terms of IP_3 performance. Use this as a benchmark when testing your receivers.

Table 1--Receivers Tested.

Manufacturer	**Model**	**P_AdBm**	**P_{IM} dBm @ S-**	**IP_3dbm**
Drake	R-4C	-29	-92 @ S3	+2.5
ICOM	IC-R70	-30	-96 @ S1	+3.0
ICOM	IC-765	-29	-93 @ S2	+3.0
ICOM	IC-781	-19	-95 @ S1	+19
Kenwood	R599D	-50	-107 @ S1	-21.5
Kenwood	TS-830S	-42	-107 @ S1	-9.5

For more insight on IMD characteristics, try switching the test receiver's preamplifier on, if it has one, and rerunning the tests. You should have noticed the IP_3 decrease by a value approximately equal to the gain the preamp added. This is a good reason for leaving the preamplifier off. In a like manner, try the same routine but this time switch on the receiver's attenuator. The IP_3 should have increased at the detriment of the receiver' sensitivity. You may notice that either of the two IMD products ($2F1$–$F2$ or $2F2$–$F1$) one is significantly lower than the other. This can and generally does happen in most receivers as a result of the way the IMD products add in cascaded front end stages. You should assume, however, that a receiver system can be no better than worst case (i.e. don't average the two IP_3 results).

Conclusion: I hope you have found this article interesting and useful. The techniques describe here should give you further insight into receiver design details as well as helping you select a commercial unit. Bare PC boards as well as assembled and tested units will be available soon. For more information contact the author.

Notes

[1]Ulrich L. Rohde, DJ2LR "High-Dynamic Range Active double-balanced Mixer" *Ham Radio* November 1977.
[2]Mike Gruber, WA1SVF "*QST* Product Reviews: A Look Behind the Scenes" *QST* October 1994.
[3]Joe Reisert, W1JR "High Dynamic Range Receivers" *Ham Radio* November 1984.

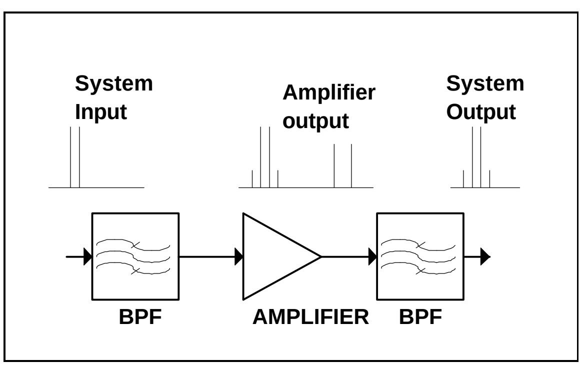
[4]Dr. Ulrich L. Rohde, DJ2LR "Recent Advances in Short Wave Receiver Design" *QST* November 1992.
[5]Jacob Makhinson, N6NWP "A High-dynamic-Range MF/HF Receiver Front End" February 1993.
[6]Dr. Ulrich L. Rohde, KA2WEU "Key Components of Modern Receiver Design—Part1" *QST* May 1994.
[7]Dr. Ulrich L. Rohde, KA2WEU "Key Components of Modern Receiver Design—Part2" *QST* June 1994.
[8]Dr. Ulrich L. Rohde, KA2WEU "Key Components of Modern Receiver Design—Part3" QST July 1994.
[9]Dr. Ulrich L. Rohde, KA2WEU "Testing and Calculation Intermodulation Distortion in Receivers" *QEX* July 1994.
[10]Dr. Ulrich L. Rohde, KA2WEU "Key Components of Modern Receiver Design: A Second Look" *QST* December 1994.
[11]Pat Hawker,G3VA G3SBI's "H-Mode Receiver Design" *Communications Quarterly* Fall 1994.

[12]**Sources:**
International Crystal Manufacturing Co., Inc. (ICM), P.O. Box 26330, 10N. Lee, Oklahoma City, OK 73126-0330 Phone: 1-(800)-725-1426. Specify a holder capacitance of 23pF and order all four crystals with a matched series resistance of 15Ω. Four crystals at the time of this writing where $40.00 including shipping.

Digi-Key Corporation, 701 Brooks Ave. South P.O. Box 677 Thief River Falls, MN, 56701-0677 Phone: 1-(800)-344-4539. All parts except crystal should be available, no minimum purchase required, service charge on orders under $25.00.

Appendix A; Why is it called third order?

The reason the particular type of distortion I have been referring to is called third order has to do with the derivation of the mathematical model for an imperfect amplifier. You will not need to be a math professor to follow this explanation, nor is it necessary that you be completely comfortable with a bunch of trigonometric relations. Just keep in mind that the ω_1 and ω_2 are the two input signals in terms of radians per second and are equivalent to $2\pi f_1$ and $2\pi f_2$. Watch what happens to these terms as the power series is expanded for the cubic (third order) term.



All amplifiers have some amount of distortion. In contrast to most general purpose wideband or video amplifiers, the output of RF or IF amplifiers are generally filtered. As shown in the amplifier configuration below, the filters effectively remove harmonically related signals caused by the non-linear behavior of the amplifier. However, the third order products are typically within the bandpass of these filters and therefor of particular concern.

If an amplifier had no distortion, its transfer function would be:

$Vout = A_0 + A_1 Vin$, Where A_0 is just the DC offset and A_1 represents the coefficient of the desired linear gain.

Because most real amplifiers do have some distortion, their transfer functions can better be represented by a power series polynomial:

$$Vout = A_0 + A_1 Vin + A_2 Vin^2 + A_3 Vin^3 + A_4 Vin^4 ....$$

For $Vin = V_1 \cos(w_1 t) + V_2 \cos(w_2 t)$, the desired first order term, $A_1 Vin$, gives the fundamental products :

$$Vout = A_0 + A_1V_1\cos(w_1t) + A_1V_2\cos(w_2t)\ .$$

The second order term, A_2Vin^2 , determines the second order products:

$$A_2Vin^2 = \frac{A_2V_1^2}{2} + \frac{a_2V_2^2}{2} +$$ the **DC Terms**

$$\frac{A_2V_1^2}{2}\cos(2w_1t) + \frac{a_2V_2^2}{2}\cos(2w_2t) +$$ the **2nd Harmonics**

$$\frac{A_2V_1V_2}{2}[\cos(w_1t + w_2t) + \cos(w_1t - w_2t)] +$$ the **2nd-order IMD**

Here is where it gets interesting, the third order term, A_3Vin^3 , gives us:

$$A_3Vin^3 = \frac{3A_3}{2}\left[V_1V_2^2 + \frac{V_1^3}{2}\right]\cos(w_1t) + \frac{3A_3}{2}\left[V_1^2V_2 + \frac{V_2^3}{2}\right]\cos(w_2t) +$$ more **Fundamental**

$$\frac{A_3V_1^3}{4}\cos(3w_1t) + \frac{A_3V_2^3}{4}\cos(3w_2t) +$$ **3rd Harmonics**

$$\boxed{\frac{3A_3V_1^2V_2}{4}\left[\cos(2w_1t + w_2t) + \cos(2w_1t - w_2t)\right] +}$$ **3rd-Order IMD product**

$$\boxed{\frac{3A_3V_1V_2^2}{4}\left[\cos(2w_2t + w_1t) + \cos(2w_2t - w_1t)\right]}$$ **3rd-Order IMD product**

The difference terms in the 3rd-order products are the trouble makers and they usually turn up right next to a weak signal you are trying to copy. Notice that as the amplifier approaches the ideal, the coefficients (A_2, A_3,... A_n) would approach zero.

---

308 Nevada Street
Redwood City CA 94062
650/369-0575
stuart@valon.net

ÿÿ