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Predicting Third Order Intermod

Since the beginning of channelized FM, the problems of 3rd order intermodulation distortion have become of major importance to the VHF operator in the heavily populated metropolitan areas. The problem of intermodulation distortion is not a new problem. It has always been with us but has not been dealt with sufficiently since analysis has been complicated and ineffective. The procedure which follows deals with the understanding and analysis of 3rd order intermodulation distortion using a method called the intercept point.

Simply stated, intermodulation distortion is caused by signals from other transmitters in band which mix somewhere in the receiver and produce interfering signals. These mixing products in the case of third order intermodulation are related to the interfering signals by the relationship $2f_1 - f_2$ and $2f_2 - f_1$, where f_1 and f_2 are the two unwanted in-band signals. These new frequencies are properly referred to as third order intermodulation distortion products (IM). The two input signals will mix and produce two additional unwanted frequencies within the receiver. Once generated they remain in the system. The problem must be solved at the point of mixing. There are other products present but only the 3rd order products will be analyzed here since they are the most troublesome.

Fortunately, the problem is not as complicated as it appears. Most of the intermod is generated because the designer uses a marginal device, or chooses a good device and biases it improperly. For example, he may choose a transistor and bias it for the lowest possible noise figure and accept the resulting gain compression, or non-linearity of gain. This non-linearity of gain is responsible for the generation of spurious responses which we shall see later. The gain compression describes the useful dynamic range of a device at the high end, just as the noise figure describes the useful range at the low end.

Third Order IM

The photo shows what happens when two signals of equal amplitude are fed into our test amplifier. Each signal has a power level of −60 dBm. The two larger signals, f_1 and f_2, are at 145.5 MHz and 146 MHz, respectively. When fed into our amplifier, two new signals are generated. Both signals are 50 dB below the two main signals for a given input power of −60 dBm.

The first signal on the left is at 145 MHz and is generated by $2f_1 - f_2 = (2)(145.5) - 146$. The last signal on the right is at 146.5 MHz and was generated by mixing $2f_2 - f_1 = (2)(146) - 145.5$.

Remember that these two new signals are not present in the air. They were generated by the mixing action of the amplifier when the two signals of 145.5 MHz and 146 MHz were injected into the amplifier simultaneously. Considering all the transmitters on the air in a given area, it is not a wonder that your receiver sometimes acts strange. Rather than try to calculate all the possible combinations of signals that may be bothering you, it may be wise to consult one of the many computer readouts available. One of the best appeared in *73* in April, 1971, by W6YAN.[1]

Understanding Gain Compression

The more linear a device, the less is the chance of generating IM. The graph of Fig. 1 is a log-log plot of input versus output power for an rf amplifier stage with 20 dB of gain. The graph shows that for an increase in input power the output should increase accordingly. Let us assume that we increase the input power by 3 dB; then the output should also increase by 3 dB. As long as this relationship is maintained, the amplifier is said to be linear. The point of non-linearity is referred to as the 1 dB compression point. This point can be found on the graph as that point where increasing our input signal by 3 dB only causes a 2 dB increase in power output.

So far, we have determined the mathematical relationship of the IM and have observed the IM products. We have defined gain compression and briefly singled it out as a major cause of IM. In the next few minutes we shall see how to accurately predict IM.

The Intercept Point

Electronic engineers in the communications field have for years used a method to accurately classify and predict the IM in amplifiers and mixers. This method is called the intercept point. The first mention of the intercept point is in an article from *Electronic Design* in 1967 upon which I have drawn heavily.[2] The original work on this concept as far as I can determine seems to have been developed at Avantek. The intercept point is a fictitious point. In actual measurement concept, the intercept point is that point at which the extrapolated linear portion of our gain plot intercepts with a plot of our IM. The gain plot is extrapolated because at high levels it deviates from a straight line because of gain compression.

The plot of Fig. 2 shows a pair of straight lines plotted on a log-log scale. It is an expansion of Fig. 1, which showed the gain plot and its compression. The third order line has been added. This line indicates the relative strength of the internally generated responses or IM for any given power input.

In actual laboratory practice, the third order IM is measured at some convenient power level using a spectrum analyzer, Fig. 4.

Referring to the photograph, we observe that the IM products are 50 dB below the fundamental signals for two signals of −60 dBm input. In Fig. 2 the distance from the fundamental line down 50 dB for a −60 dBm input signal has been plotted and this distance labeled "X".

The intercept line can be drawn horizontally across the graph at a point one-half times from the −60 dBm input signal. The point at which the intercept line crosses the fundamental gain line is the intercept point.

The third order IM line can now be drawn so that the measured point and the intercept point form a straight line. When talking about the intercept point it is common usage to refer to the output intercept point. It is possible, and sometimes convenient, to specify the amplifier performance in terms of its input intercept point.

For all practical purposes, our plot is complete. We can now predict what the IM will be for any given input signal. (Example: For two input signals of −80 dBm, third order IM is 90 dB below the carrier.)

Third order IM 50 dB down. F1=145.5; F2=146; F1 and F2 at −60 dBm input.

If you stare at Fig. 2 long enough, you will realize that by changing the input level by 1 dB the IM will change by 2 dB. Our original measurement produced an IM of 50 dB down for 2 signals of –60 dBm input. Therefore, by decreasing our input signals 20 dB to a new level of –80 dBm, we have improved our IM products by 40 dB and our new level is 90 dB down for 2 signals of –80 dBm input.

Rule Of Thumb

In the absence of a spectrum analyzer, a reasonable and accurate plot of the third order IM products can be obtained by assuming that the intercept line is approximately 8 dB to 15 dB above the 1 dB compression point with 10 dB being a good guess. This assumption will produce an error of 2 dB for each 1 dB we are off in our assessment. Care must also be used in making the 1 dB gain compression measurement for the same reason.

After carefully measuring the 1 dB compression point of the amplifier, plot the gain line on your graph and note the 1 dB point. Approximately 10 dB above the 1 dB point, draw a horizontal line across the graph. We are now reconstructing Fig. 2 backwards. From the horizontal intercept line note the number of dB to the gain line at any input signal level you choose. For this same input level plot a point twice that number of dB down from the gain line. This is the amount of 3rd order intermodulation distortion in your amplifier at the input level you have chosen. You now have one IM point on your chart and the intercept point and can now draw a straight line between these two points and complete your graph.

Unequal Signal Levels

Almost all manufacturers of rf amplifiers now include the intercept point as part of the data on the spec sheet. As we have just seen, the intercept point is measured using two signals of equal power. Unfortunately, this is usually not the case in an actual system. One signal is likely to be from a strong nearby transmitter and the other from a source quite a distance away. When the amplitudes of the two signals are known and they are not the same power level, they can be converted to two signals of equal amplitude quite simply. In this case, take the stronger of the two signals and subtract from it one-third of the difference between the two signals. This calculation equalizes the two signals and generates the same worst case IM as the two unequal signals.[3] (Example: One signal is at –40 dBm and another at –70 dBm. The difference between the two signals is 30 dB. One-third of 30 dB is 10 dB, which when subtracted

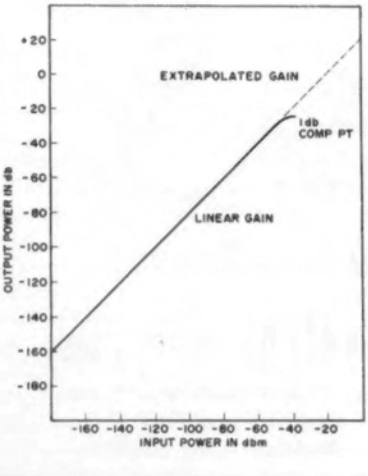

Fig. 1. Linear gain and the 1 dB compression point.

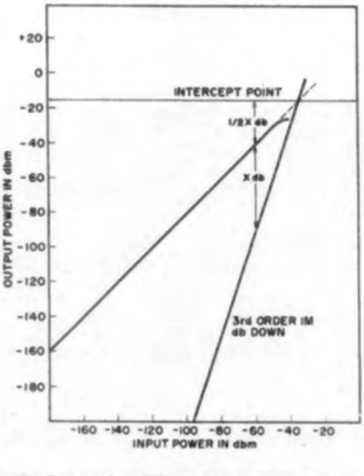

Fig. 2. 3rd order IM vs input power using the intercept point.

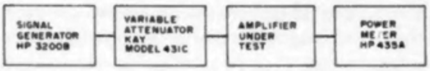

Fig. 3. Test set-up to determine amplifier 1 dB compression point.

from −40 dB yields an equivalent of two equal signals of −50 dB.)

Additional Calculations

There are still many amplifier manufacturers who do not use the intercept point and simply specify the 3rd order IM as being so many dB down for a given two signal input level. When using this type of data, it is convenient to be able to convert to the intercept point quickly without resorting to the graphical analysis. Presented here are some formulas which have been derived from the graphical analysis. They may be used by themselves or as an aid in preparing a graphic presentation. The pertinent terms are the input intercept point or IIP, the output intercept point or OIP, the amplifier gain, and the third order IM for a given two signal input.

$$\text{IIP} = \tfrac{1}{2}\,\text{IM} + \text{Signal in}$$

$$\text{OIP} = \text{IIP} + \text{Amplifier Gain}$$

Combining these two equations

$$\text{OIP} = \text{Amplifier Gain} + \tfrac{1}{2}\,\text{IM} + \text{Signal in}$$

By rearranging these terms the IM can be calculated directly.

$$\text{IM} = [\text{OIP} - (\text{Amplifier Gain} + \text{Signal in})] \quad (2)$$

Remember that the OIP is approximately 10 dB above the 1 dB compression point. Therefore if only the 1 dB compression point is given, the problem may still be solved by substituting the 1 dB compression point +10 dB for the OIP.

Analyzing Your IM Problem

From all our observations, we can see that if IM is a problem, one or more of the transistor stages is probably operating with a low 1 dB compression point. The obvious solution is to try to make the transistors run as linearly as possible and raise the compression point. As I stated earlier, many transistors are biased for lowest noise figure and the resultant gain compression is accepted. If the transistor is not being operated near its maximum power dissipation, a little more collector current might do the job. Be careful not to over dissipate the transistor. A better choice would be to choose a new transistor, one which is capable of higher linear output power. Some of the new CATV devices work great, because they were designed for low IM and good noise figure.

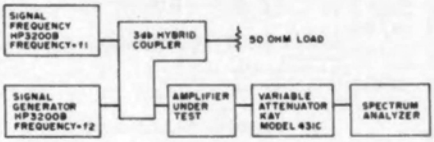

Fig. 4. Test set-up for 3rd order intermodulation distortion measurements. Note: It is very possible to overload the spectrum analyzer and generate intermodulation distortion in the analyzer itself. It is therefore a good idea to include an attenuator between the amplifier and the analyzer. Always use the lowest possible signal level to the amplifier to generate IM when making this measurement.

A good project would be to collect as many data sheets as possible on devices which might be useful at your frequency of interest and compare the optimum NF and required current. Some types such as the 2N5109 are specified as 3 dB max. noise figure at 200 MHz with 10 mA.

> **Somewhat higher priced types (MS-175, K6001) will give 1.5 dB NF at 15 mA at 150 MHz. In a feedback amplifier, gain is 15 dB and the output compression point is over 20 milliwatts. At 2 mW out, that is, two two-milliwatt signals the in-band intermodulation product (third order product) is more than 40 dB down. Such an amplifier is still operating with good linearity when succeeding stages are overloading, and therefore, there is little point in worrying about how to further improve the first stage.**[4]

I have quoted the above paragraph because it sums up nicely everything that I wanted to say and includes a fine problem. All the information needed to complete a graph of the IM plot is present. The gain at 15 dB for our gain line and the 1 dB compression at 20 mW or +13 dB out. If we again assume the intercept point line to be approximately 10 dB above our 1 dB com-

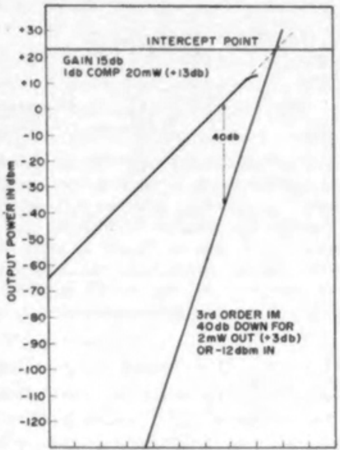

Fig. 5. Solution to IM problem given in text. Note: This graph has been plotted using the information quoted in the text. The only assumption made was that the intercept point was 10 dB above the 1 dB compression point. The graph shows that the amplifier has an output intercept point of +23 dBm or an input intercept point of +8 dBm.

pression point, we can plot a graph of third order IM products and see that the results agree favorably with the IM statement given at an output level of 2 mW or +3 dB. When analyzing this problem remember that the IM statement given was for an output level of 2 mW or +3 dB. So as not to confuse things, it might be easier to work with an input level of −12 dBm, which is the input level required to give an output of +3 dB in an amplifier with 15 dB of gain.

Comparing Two Amplifiers

With the formulas derived from the graphical analysis we can now compare amplifier performance. The amplifiers of Figs. 2 and 5 can now be compared quickly since both have been characterized by the intercept point. The input level I have chosen is for a signal level of −73 dBm or 50 microvolts. In the old day of AM this represented an S9 signal and I suppose it is as good a place as any to establish a reference input. The data we need to work with is only the amplifier gain and the intercept point. Since we have graphed both amplfiers, we can look up the IM on the graph at the −73 dBm input point or we can solve the problem mathematically, assuming that the manufacturer has provided the intercept point.

Fig. 2.
AMPLIFIER SPECIFICATIONS
Gain = 20 dB
OIP = −15 dBm

Fig. 5.
AMPLIFIER SPECIFICATIONS
Gain = 15 dB
OIP = +23 dBm

Problem: Calculate 3rd order IM at input level of −73 dBm.
Solution:

Fig. 2.

$$\begin{aligned} IM &= [OIP - (Gain + Signal\ in)]\ (2) \\ &= [(-15) - (20) + (-73)]\ (2) \\ IM &= 76\text{ dB down} \end{aligned}$$

Fig. 5.

$$\begin{aligned} IM &= [OIP - (Gain + Signal\ in)]\ (2) \\ &= [(+23) - (15) + (-73)]\ (2) \\ IM &= 162\text{ dB down} \end{aligned}$$

(Note: Fig. 5 must be expanded to read this IM value.)

There is no contest in this case and the amplifier of Fig. 5 wins easily.

Assuming that your receiver is ideal and generates no IM, let's see what happens when the preamplifier of Fig. 2 is placed ahead of the receiver. First, the two input signals of −73 dBm are amplified by 20 dB, which is the gain of the amplifier. The signals at the output of the amplifier are now −53 dBm, which is applied to the receiver input. In addition, the IM generated in the amplifier is 76 dB below our −53 dBm output signals or at a signal level of −129 dBm. This would be a very marginal amplifier since most good receivers can begin to hear at −129 dBm or .08 uV. Remember, we are analyzing this system at a 50 uV input level so signals of 20 dB over S9 could easily cause problems. The fact that we have added 20 dB of gain to our system will probably cause IM to be generated further on down the receiver. These solutions can therefore be carried through a receiver right through the i-f stages. If you do decide to improve the intermod don't get carried away. It usually takes two people to solve these problems – one to do the actual work and another to tell him when to stop.

Conclusion

The same procedures can be used to accurately predict other orders of IM and are dealt with in the references.

Even if you decide not to dig into your receiver (a very wise move) and try to lower its IM, I hope that this article will help you next time you compare amplifier specifications.

When writing to amplifier manufacturers for data, ask them to specify the intercept point. You can then graphically analyze the amplifier and pick the one which suits you best. Remember, an amplifier with a lower noise figure will not make operating any easier if it adds IM to your system.

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