

Intermodulation Distortion Considerations for ADCs

by Walt Kester

INTRODUCTION

Intermodulation distortion (IMD) is a popular measure of the linearity of amplifiers, gain blocks, mixers, and other RF components. The second and third-order intercept points (IP2 and IP3) are figures of merit for these specifications and allow distortion products to be computed for various signal amplitudes. RF engineers are quite familiar with these specifications, but confusion can arise when applying them to ADCs. This tutorial first defines IMD with respect to ADCs and then points out the precautions which must be taken when applying the definitions of IP2 and IP3 to ADCs.

TWO TONE INTERMODULATION DISTORTION (IMD)

Two tone IMD is measured by applying two spectrally pure sinewaves to the ADC at frequencies f_1 and f_2 , usually relatively close together. The amplitude of each tone is set slightly more than 6 dB below full-scale so that the ADC does not clip when the two tones add in-phase. The location of the second and third-order products are shown in Figure 1. Notice that the second-order products fall at frequencies which can be removed by digital filters. However, the third-order products $2f_2 - f_1$ and $2f_1 - f_2$ are close to the original signals and are more difficult to filter. Unless otherwise specified, two-tone IMD refers to these "close-in" third-order products. It is customary to specify the value of the IMD product in dBc relative to the value of *either* of the two original tones, and not to their sum.

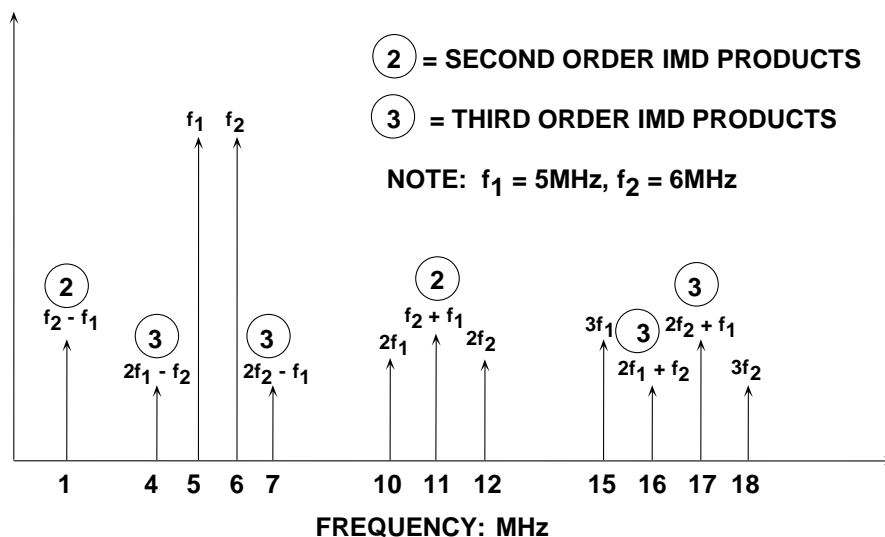


Figure 1: Second and Third-Order Intermodulation Products for $f_1 = 5\text{ MHz}$, $f_2 = 6\text{ MHz}$

Note, however, that if the two tones are close to $f_s/4$, then the aliased third harmonics of the fundamentals can make the identification of the actual $2f_2 - f_1$ and $2f_1 - f_2$ products difficult. This is because the third harmonic of $f_s/4$ is $3f_s/4$, and the alias occurs at $f_s - 3f_s/4 = f_s/4$. Similarly, if the two tones are close to $f_s/3$, the aliased second harmonics may interfere with the measurement. The same reasoning applies here; the second harmonic of $f_s/3$ is $2f_s/3$, and its alias occurs at $f_s - 2f_s/3 = f_s/3$.

SECOND AND THIRD-ORDER INTERCEPT POINTS (IP2, IP3), 1-dB COMPRESSION POINT

Third-order IMD products are especially troublesome in multi-channel communications systems where the channel separation is constant across the frequency band. Third-order IMD products can mask out small signals in the presence of larger ones.

In amplifiers, mixers, and other RF components, it is common practice to specify the third-order IMD products in terms of the *third order intercept point* (IP3) as is shown by Figure 2. Two spectrally pure tones are applied to the system. The output signal power in a single tone (in dBm) as well as the relative amplitude of the third-order products (referenced to a single tone) are plotted as a function of input signal power. The fundamental is shown by the *slope = 1* curve in the diagram. If the system nonlinearity is approximated by a power series expansion, it can be shown that second-order IMD (IMD2) amplitudes increase 2 dB for every 1 dB of signal increase, as represented by the *slope = 2* curve in the diagram.

Similarly, the third-order IMD (IMD3) amplitudes increase 3 dB for every 1-dB of signal increase, as indicated by the *slope = 3* plotted line. With a low level two-tone input signal, and two data points, one can draw the second and third order IMD lines as they are shown in Figure 2 (using the principle that a point and a slope define a straight line).

Once the input reaches a certain level however, the output signal begins to soft-limit, or compress. A parameter of interest here is the *1-dB compression point*. This is the point where the output signal is compressed 1 dB from an ideal input/output transfer function. This is shown in Figure 2 within the region where the ideal *slope = 1* line becomes dotted, and the actual response exhibits compression (solid).

Nevertheless, both the second- and third-order intercept lines may be extended, to intersect the (dotted) extension of the ideal output signal line. These intersections are called the *second* and *third-order intercept points*, respectively, or IP2 and IP3. These power level values are usually referenced to the output power of the device delivered to a matched load (usually, but not necessarily 50 Ω) expressed in dBm.

It should be noted that IP2, IP3, and the 1-dB compression point are all a function of frequency, and as one would expect, the distortion is worse at higher frequencies.

For a given frequency, knowing the third order intercept point allows calculation of the approximate level of the third-order IMD products as a function of output signal level.

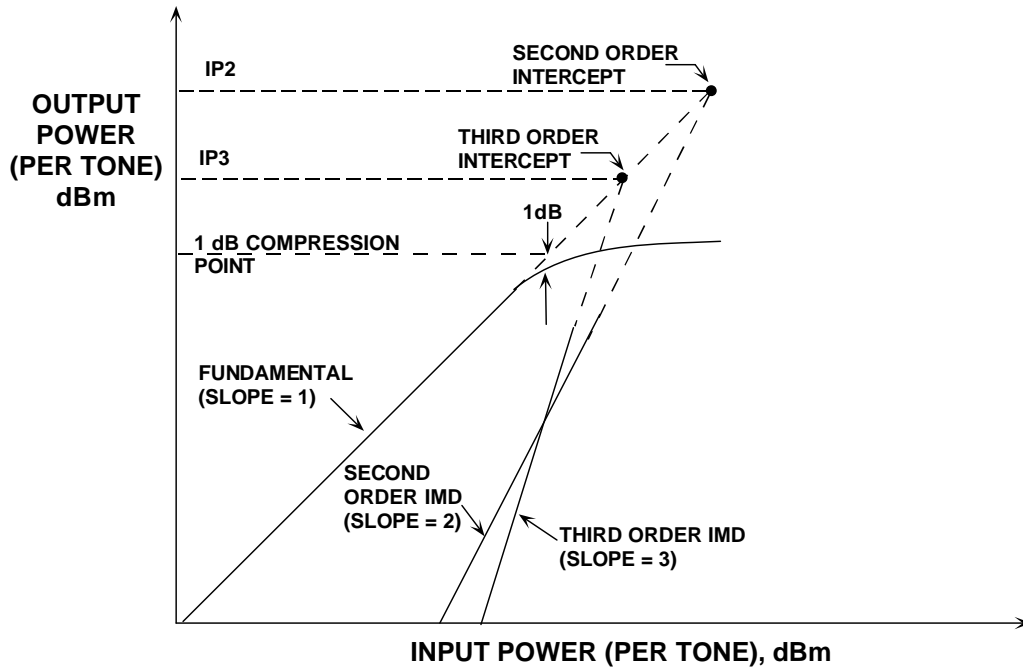


Figure 2: Definition of Intercept Points and 1-dB Compression Points for Amplifiers

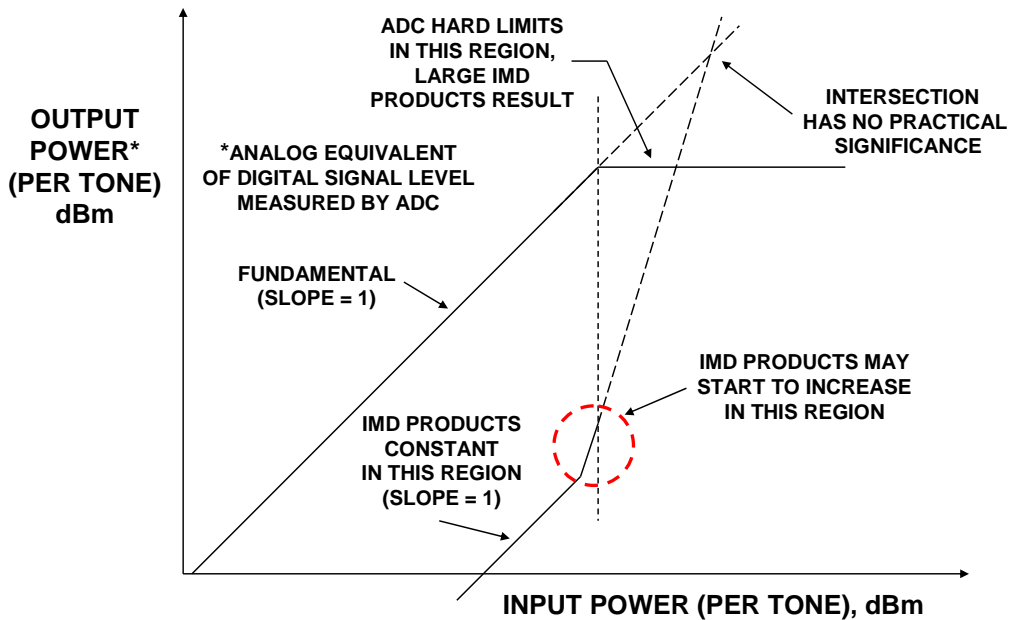


Figure 3: Intercept Points for Data Converters Have No Practical Significance

The concept of *second- and third-order intercept points* is not valid for an ADC, because the distortion products do not vary in a predictable manner (as a function of signal amplitude). The ADC does not gradually begin to compress signals approaching full-scale (there is no 1-dB compression point); it acts as a *hard limiter* as soon as the signal exceeds the ADC input range, thereby suddenly producing extreme amounts of distortion because of clipping. On the other

hand, for signals much below full-scale, the distortion floor remains relatively constant and is independent of signal level. This is shown graphically in Figure 3.

The IMD curve in Figure 3 is divided into three regions. For low level input signals, the IMD products remain relatively constant regardless of signal level. This implies that as the input signal increases 1 dB, the ratio of the signal to the IMD level will increase 1 dB also. When the input signal is within a few dB of the ADC full-scale range, the IMD may start to increase (but it might not in a very well-designed ADC). The exact level at which this occurs is dependent on the particular ADC under consideration—some ADCs may not exhibit significant increases in the IMD products over their full input range, however most will. As the input signal continues to increase beyond full-scale, the ADC should function acts as an ideal limiter, and the IMD products become very large. For these reasons, the 2nd and 3rd order IMD intercept points are not specified for ADCs. It should be noted that essentially the same arguments apply to DACs. In either case, the single- or multi-tone SFDR specification is the most accepted way to measure data converter distortion.

MULTI-TONE SPURIOUS FREE DYNAMIC RANGE

Two-tone and multi-tone SFDR are often measured in communications applications. The larger number of tones more closely simulates the wideband frequency spectrum of cellular telephone systems such as AMPS or GSM. Figure 4 shows the 2-tone intermodulation performance of the [AD9444](#) 14-bit, 80-MSPS ADC. The input tones are at 69.3 MHz and 70.3 MHz and are located in the second Nyquist Zone.

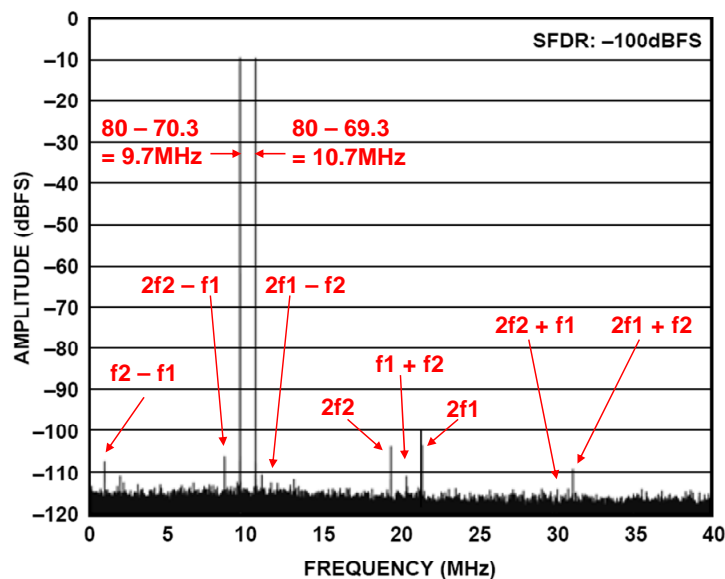


Figure 4: [AD9444](#) 14-Bit 80-MSPS ADC Two-Tone FFT for $f_1 = 69.3$ MHz and $f_2 = 70.3$ MHz Input Tones

The aliased tones therefore occur at 9.7 MHz and 10.7 MHz in the first Nyquist Zone. Figure 4 also shows the location of all the aliased IMD products. High SFDR increases the receiver's ability to capture small signals in the presence of large ones, and prevents the small signals from

being masked by the intermodulation products of the larger ones. Figure 5 shows the AD9444 two-tone SFDR as a function of input signal amplitude for the same input frequencies.

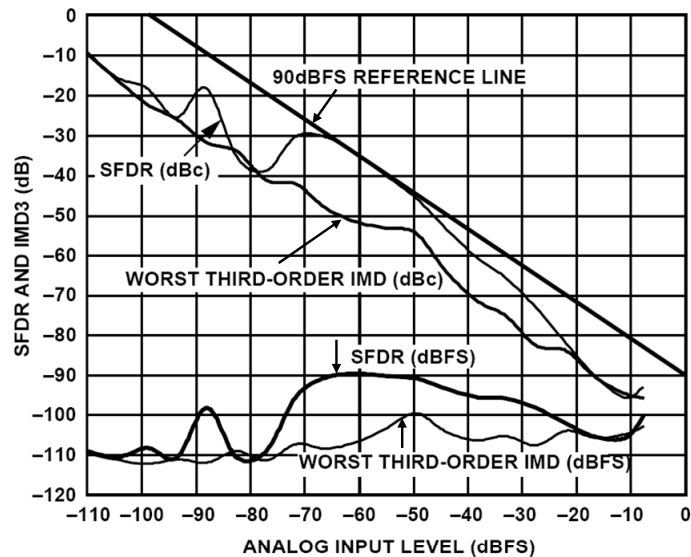


Figure 5: Two-Tone SFDR and Worst IMD3 Product vs. Input Amplitude for AD9444 14-bit, 80-MSPS ADC

SUMMARY

Intermodulation distortion (IMD2, IMD3) and intercept points (IP2, IP3) are well understood specifications for RF components such as mixers, LNAs, gain blocks, and amplifiers. The nonlinearity of these devices is modeled by a power series expansion, and distortion levels for various signal amplitudes can be predicted from the intercept points IP2 and IP3. Unlike amplifiers and mixers, ADC distortion (especially for low level signals) does not follow the simple power series expansion model, so the intercept points IP2 and IP3 are not useful in predicting distortion performance. In addition, ADCs act as ideal limiters when input signals exceed full-scale, while amplifiers and mixers generally act as soft limiters.

In spite of these differences, however, it is critical to know the two-tone IMD performance of ADCs used in communications applications. A good data sheet will present this data for a large number of input signal frequencies and amplitudes. In addition, the [ADIsimADC™](#) program can be very useful in evaluating various ADCs at the specific frequencies and amplitudes required in the system application. The ADIsimADC program acts as a virtual evaluation board and can be downloaded from the Analog Devices' website along with the most recent models for IF-sampling ADCs. The program uses an FFT engine and gives accurate SNR, SFDR, and IMD results for both single and dual-tone input signals.

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