Wideband A/D Converter Front-End Design Considerations
When to Use a Double Transformer Configuration

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BACKGROUND

Transformers are used for isolation and to convert signals from single-ended to differential. A factor often overlooked when using transformers in the front-end circuitry of high-speed A/D converters is that they are never ideal. With sinusoidal input signals, any imbalance introduced by the transformer delivers an imperfect sinusoidal wave to the input of the ADC, and results in overall data-conversion performance worse than the ADC could otherwise provide. We consider here the effects of input imbalances on ADC performance and provide examples of circuitry to achieve improved results.

About Transformers

The wide variety of available models from many manufacturers can make transformer selection a confusing process. The challenge is compounded by the differing approaches taken by suppliers in specifying performance; they often differ in the choice and definitions of the parameters they specify.

Some key parameters to consider when selecting a transformer to drive a particular ADC are insertion loss, return loss, magnitude imbalance, and phase imbalance. *Insertion loss* is a guide to the bandwidth capability of the transformer. *Return loss*, also useful, allows the user to design the termination to match the transformer's response at a particular frequency or band of frequencies—especially important when using transformers with greater than unity turns ratios. We will focus here on *magnitude-* and *phase imbalance*, and how they affect the ADC's performance in high-bandwidth applications.

Theoretical Analysis

Even with a wide bandwidth rating, the coupling between the transformer's single-ended primary and differential secondary, though linear, introduces magnitude- and phase imbalances. When applied to a converter (or other differential-input device), these imbalances worsen even-order distortion of the converted (or processed) signal. While usually negligible at low frequencies, this added distortion in high-speed converters becomes significant at roughly 100 MHz. Let us first examine how the magnitude- and phase imbalance of a differential-input signal, particularly the second-harmonic distortion, affect the performance of an ADC.
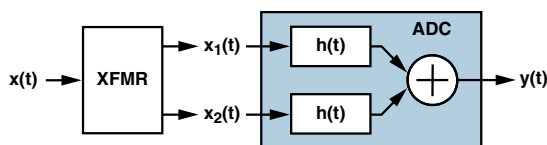

Figure 1. Simplified block diagram of the ADC front end using a transformer.

Consider the input, $x(t)$, to the transformer. It is converted into a pair of signals, $x_1(t)$ and $x_2(t)$. If $x(t)$ is sinusoidal, the differential output signals, $x_1(t)$ and $x_2(t)$, are of the form

$$x_1(t) = k_1 \sin(\omega t)$$
$$x_2(t) = k_2 \sin(\omega t - 180° + \varphi) = -k_2 \sin(\omega t + \varphi) \tag{1}$$

The ADC is modeled as a symmetrical third-order transfer function:

$$h(t) = a_0 + a_1 x(t) + a_2 x^2(t) + a_3 x^3(t) \tag{2}$$

Then

$$y(t) = h(x_1(t)) - h(x_2(t))$$
$$y(t) = a_1\left[x_1(t) - x_2(t)\right] + a_2\left[x_1^2(t) - x_2^2(t)\right] + a_3\left[x_1^3(t) - x_2^3(t)\right] \tag{3}$$

Ideal Case—No Imbalance

When $x_1(t)$ and $x_2(t)$ are perfectly balanced, they have the same magnitude ($k_1 = k_2 = k$) and are exactly 180° out of phase ($\varphi = 0°$). Since

$$x_1(t) = k \sin(\omega t)$$
$$x_2(t) = -k \sin(\omega t) \tag{4}$$

$$y(t) = 2a_1 k \sin(\omega t) + 2a_3 k^3 \sin^3(\omega t) \tag{5}$$

Applying the trigonometric identity for powers and gathering terms of like frequency,

$$y(t) = 2\left(a_1 k + \frac{3a_3 k^3}{4}\right)\sin(\omega t) - \left(\frac{a_3 k^3}{4}\right)\sin(3\omega t) \tag{6}$$

This is the familiar result for a differential circuit: even harmonics cancel for ideal signals, while odd harmonics do not.

Magnitude Imbalance

Now suppose the two input signals have a magnitude imbalance, but no phase imbalance. In this case, $k_1 \neq k_2$, and $\varphi = 0$.

$$x_1(t) = k_1 \sin(\omega t)$$
$$x_2(t) = -k_2 \sin(\omega t) \tag{7}$$

Substituting Equation 7 in Equation 3 and again applying the trigonometric power identities,

$$y(t) = \frac{a_2}{2}\left(k_1^2 - k_2^2\right) + \left(a_1(k_1 + k_2) + \frac{3a_3}{4}\left(k_1^3 + k_2^3\right)\right)\sin \omega t$$
$$- \left(\frac{a_2}{2}\left(k_1^2 - k_2^2\right)\right)\cos 2\omega t - \left(\frac{a_3}{4}\left(k_1^3 + k_2^3\right)\right)\sin 3\omega t \tag{8}$$

We see from Equation 8 that the second harmonic in this case is proportional to the difference of the squares of the magnitude terms, k_1 and k_2, viz.,

$$2^{nd}\ harmonic \propto k_1^2 - k_2^2 \tag{9}$$

Phase Imbalance

Assume now that the two input signals have a phase imbalance between them, with no magnitude imbalance. Then, $k_1 = k_2$, and $\varphi \neq 0$.

$$x_1(t) = k_1 \sin(\omega t)$$
$$x_2(t) = -k_1 \sin(\omega t + \varphi) \tag{10}$$

Substituting Equation 10 in Equation 3 and simplifying,

$$\begin{aligned}
y(t) = & \left(a_1 k_1 + \frac{3 a_3 k_1^3}{4} \right) \left(\sin \omega t + \sin \omega t \cos \varphi + \cos \omega t \sin \varphi \right) \\
& - \left(\frac{a_2 k_1^2}{2} \right) \left(\cos 2\omega t - \cos 2\omega t \cos 2\varphi + \sin 2\omega t \sin 2\varphi \right) \\
& - \left(\frac{a_3 k_1^3}{4} \right) \left(\sin 3\omega t - \sin 3\omega t \cos 3\varphi + \cos 3\omega t \sin 3\varphi \right)
\end{aligned} \tag{11}$$

From Equation 11, we see that the second-harmonic amplitude is proportional to the square of the magnitude term, k.

$$2^{nd}\ harmonic \propto k_1^2 \tag{12}$$

Observations

A comparison of Equation 9 and Equation 12 shows that the second-harmonic amplitude is more severely affected by phase imbalance than by magnitude imbalance. For phase imbalance, the second harmonic is proportional to the square of k_1, while for magnitude imbalance, the second harmonic is proportional to the difference of the squares of k_1 and k_2. Since k_1 and k_2 are approximately equal, this difference is small.

As a test of the validity of these calculations, MATLAB code was written for the model described above to quantify and illustrate the impact of magnitude- and phase imbalances on harmonic distortion of a high-performance ADC with a transformer input (Appendix A). The model includes additive white Gaussian noise.

The coefficients, a_i, used in the MATLAB model are for the AD9445, a high-performance 16-bit, 125-MSPS ADC. The AD9445, in the front-end configuration shown in Figure 2, was used to generate the FFT shown in Figure 3, from which the coefficients were derived.
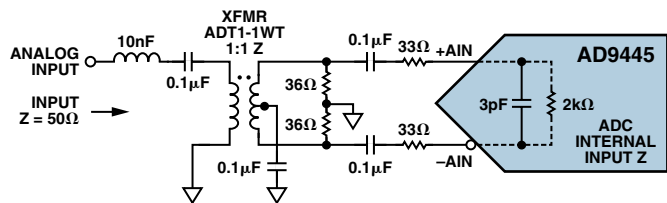

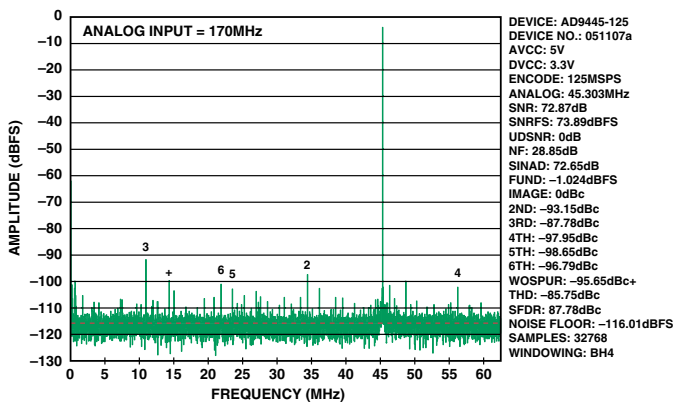Figure 2. Front-end configuration of the AD9445 with transformer.

Figure 3. Typical FFT of AD9445, 125 MSPS, IF = 170 MHz.

The noise floor, second harmonic, and third harmonic here reflect the composite performance of the converter and front-end circuitry. The converter distortion coefficients (a_2 and a_3) and noise were computed using these measured results, combined with the 0.0607 dB of magnitude imbalance and 14° of phase imbalance at 170 MHz, specified for a standard 1:1 impedance ratio transformer.

These coefficients are used in Equation 8 and Equation 11 to compute $y(t)$, while the magnitude- and phase imbalances are varied in the ranges 0 V to 1 V and 0 degrees to 50 degrees, respectively (the imbalance ranges of a typical transformer in the 1-MHz-to-1000-MHz range), and observe the effect on the second harmonic. The results of the simulations are shown in Figure 4 and Figure 5.
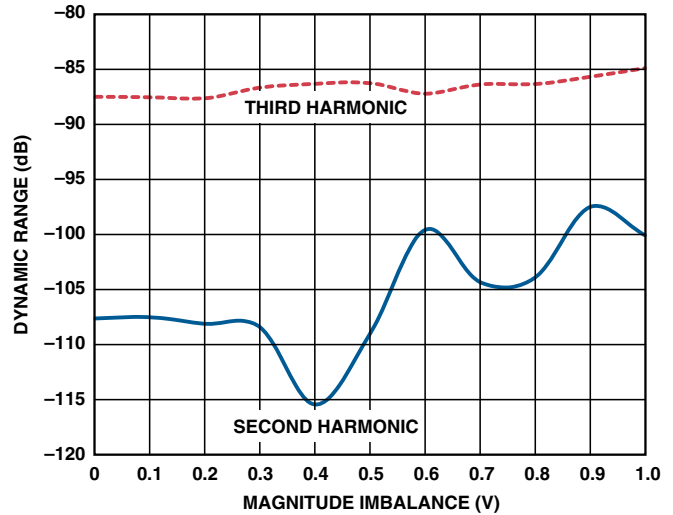

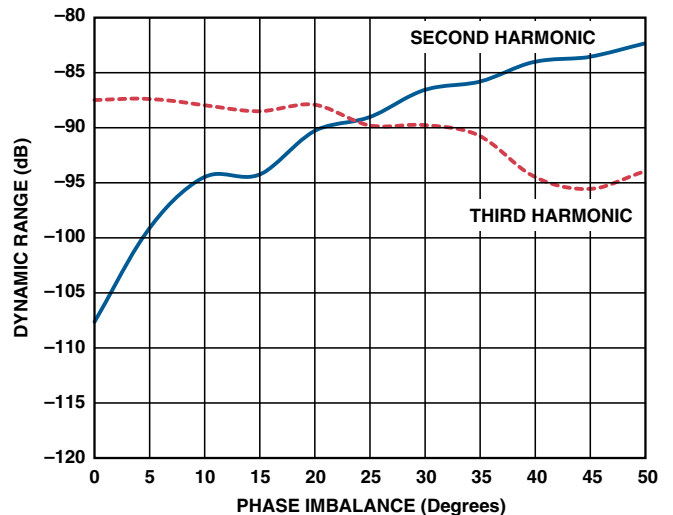Figure 4. Harmonics plotted vs. *magnitude* imbalance only.

Figure 5. Harmonics plotted vs. *phase* imbalance only.

Figure 4 and Figure 5 show that (a) the third harmonic is relatively insensitive to both magnitude- and phase imbalance, and (b) that the second harmonic deteriorates more rapidly with phase imbalance than with magnitude imbalance. Thus, to achieve better performance from the ADC, a transformer configuration with improved phase imbalance is needed. Two feasible configurations, the first involving a double balun, and the second a double transformer, are shown in Figure 6 and Figure 7.
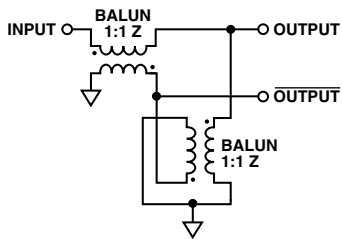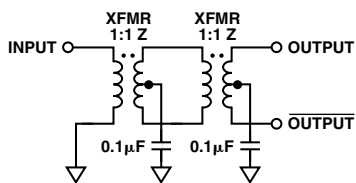
Figure 6. Double balun configuration.

Figure 7. Double transformer configuration.

The imbalances from these configurations were compared using a vector network analyzer on specially designed characterization boards. Figure 8 and Figure 9 compare the magnitude- and phase imbalance of these configurations with that of a single transformer.
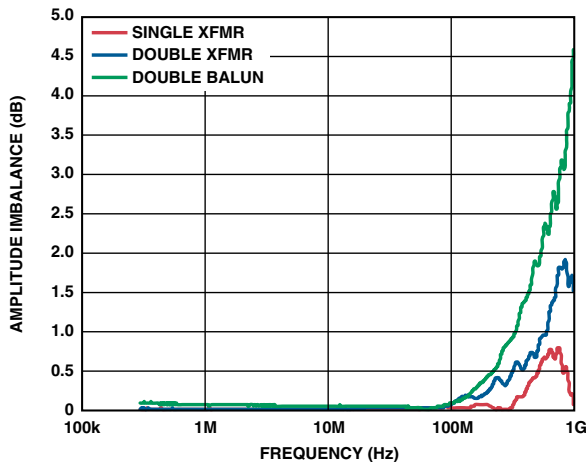

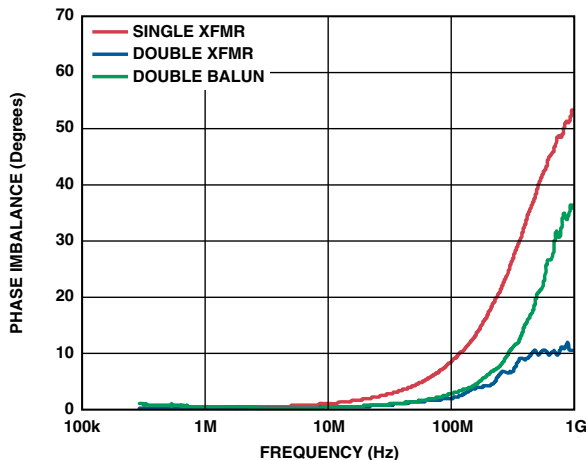Figure 8. Magnitude imbalance from 1 MHz to 1000 MHz.

Figure 9. Phase imbalance from 1 MHz to 1000 MHz.

The above figures clearly show that the double configurations have better phase imbalance at the cost of slightly degraded magnitude imbalance. Therefore, using the results of the above analysis, it appears that the double-transformer configurations can be used to achieve better performance. FFT plots of

AD9445 using a single transformer input (Figure 10) and a double balun input (Figure 11) show that this is indeed the case; a +10-dB improvement in SFDR is seen with a 300-MHz IF signal.
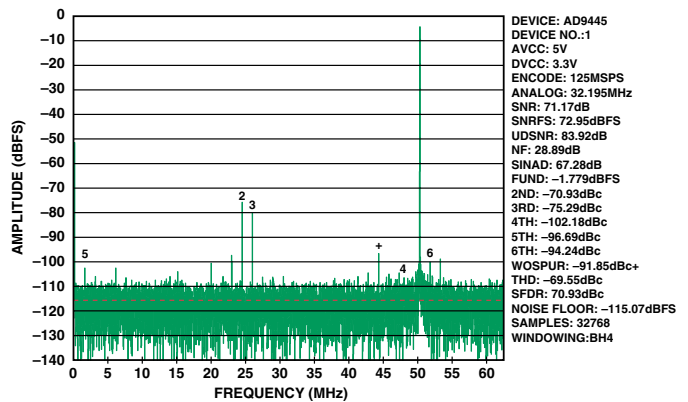

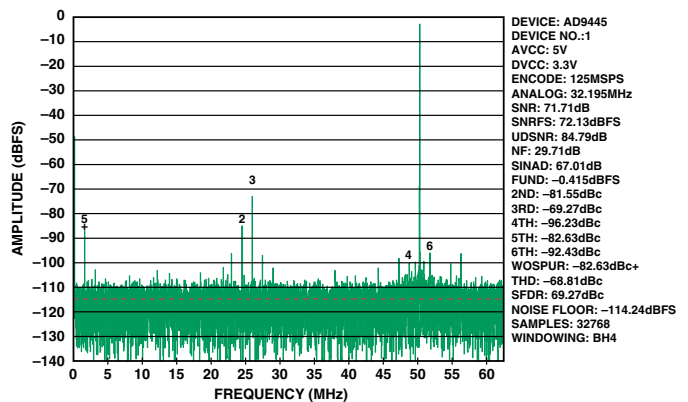Figure 10. FFT of AD9445, single transformer input, 125 MSPS, IF = 300 MHz.

Figure 11. FFT of AD9445, double balun input, 125 MSPS, IF = 300 MHz.

Does this mean that to achieve good performance one must couple two transformers or two baluns onto the ADC's front end? Not necessarily. The analysis shows that it is essential to use a transformer that has very little phase imbalance. In the following examples (Figure 12 and Figure 13), two different single transformers were used to drive the AD9238 with a 170-MHz IF signal. These examples show that there is 29-dB improvement in second harmonic when the ADC is driven by a transformer that has improved phase imbalance at high frequencies.
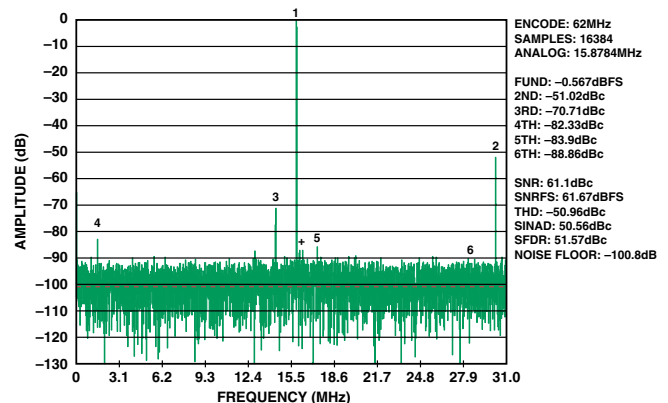

Figure 12. FFT of AD9238, single transformer input, 62 MSPS, IF = 170 MHz @ –0.5 dBFS, second harmonic = –51.02 dBc.

ENCODE: 62MHz
SAMPLES: 16384
ANALOG: 15.8746MHz

FUND: –0.504dBFS
2ND: –80.56dBc
3RD: –77.09dBc
4TH: –98.55dBc
5TH: –88.81dBc
6TH: –95.01dBc

SNR: 62.81dBc
SNRFS: 63.31dBFS
THD: –75.21dBc
SINAD: 62.57dBc
SFDR: 77.24dBc
WOSPUR: –87.21dBc
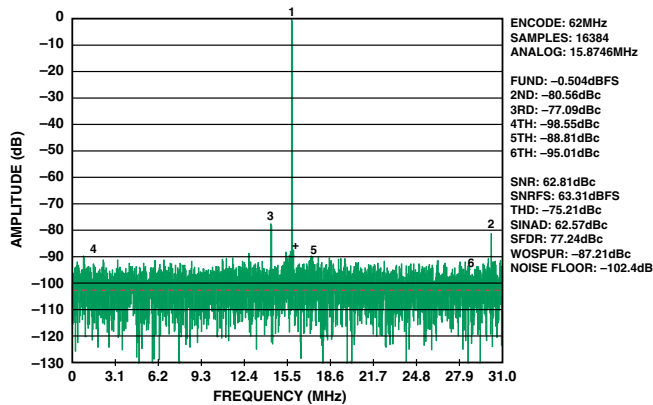NOISE FLOOR: –102.4dB

Figure 13. FFT of AD9238, single transformer input, 62 MSPS, IF = 170 MHz @ –0.5 dBFS, second harmonic = –80.56 dBc.

CONCLUSION

The phase imbalance of a transformer can worsen the second-harmonic distortion when the transformer is used as a front end for processes (such as A/D conversion, D/A conversion, and amplification) with high-IF inputs (>100 MHz). However, by employing a pair of transformers or baluns, significant improvements can be readily achieved, at the cost of an additional transformer and extra PC board space.

Single-transformer designs can achieve adequate performance if the design bandwidth is small and a suitable transformer is chosen. However, they do require a limited matching of bandwidth, and they can be expensive or physically large.

In either case, choosing the best transformer for any given application requires detailed knowledge of the transformer's specifications. Phase imbalance is of particular importance for high-IF inputs (>100 MHz). Even if it is not specified in the data sheet, most transformer manufacturers will provide phase-imbalance information upon request. A network analyzer can be used to measure the transformer's imbalances as a check, or if the information is not readily available.

ACKNOWLEDGEMENTS

FURTHER READING

1. Reeder, Rob, "Transformer-Coupled Front End for Wideband A/D Converters," *Analog Dialogue*, Vol. 39, No. 2, pp. 3-6, 2005.
2. Mini-Circuits Data Sheet ADT1-1WT.
3. Pulse Data Sheet CX2039L.
4. Mini-Circuits Application Note: "How Transformers Work."
5. The Mathworks *Matlab* program.
6. Analog Devices Data Sheet AD9445.
7. Analog Devices Data Sheet AD9238.
8. M/A-COM Data Sheet TP101.
9. Sprague-Goodman Data Sheet GLSB4R5M102.

APPENDIX A

MATLAB code used in this experiment:

```
% Matlab code to study the effect of magnitude
and phase imbalance of input
% signals on the output
% Oct 19, 2005
clear all; close all;

% Error terms that can be set by the user
magnErrdB = 0; %in dB
phaseErr = 50; %in degrees
sd_noise = 100e-6; %std dev of noise

% Convert dB magnErr to voltage level
magnErr = 10^(magnErrdB/20);

% Coefficients
a0=0; %dc offset
a1=0.89; a2=0.00038; a3=0.0007; %coefficients
of 1st,2nd,3rd harmonics
                     %to match AD9445
typical FFT

fin = 100; %input freq - does not affect
calculations
t = 0:1:2047;
%Input signals
x1 = 0.5*sin((t/2048)*2*pi*fin);
x2 = 0.5*(magnErr)*sin(((t/2048)*2*pi*fin)-pi-
(phaseErr*pi/180));
%Each differential signal multiplied by the
transfer function
y1 = a0 + a1*x1 + a2*x1.^2 + a3*x1.^3;
y2 = a0 + a1*x2 + a2*x2.^2 + a3*x2.^3;
%Output
y = y1 - y2;
noise = sd_noise*randn(1,length(y));
y = y + noise;

% figure; plot(1000*t(1:80),x1(1:80),1000*t(1:8
0),x2(1:80),1000*t(1:80),y(1:80));

%Take the FFT
fft_y = fft(y/1024, 2048);
Pyy = 10*log10(fft_y.*conj(fft_y));
freq_axis = 0:1:1023;
% figure; plot(freq_axis, Pyy(1:1024), '-d');
% title('Frequency content of the output');
% xlabel('Frequency (Hz)');
% axis tight;

%Print fundamental and 2nd, 3rd harmonics
f = Pyy(101)
h2 = Pyy(201)
h3 = Pyy(301)
```