

## Frequency Domain Response of Switched-Capacitor ADCs

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### INTRODUCTION

Knowing the frequency response of unbuffered analog-to-digital converters (ADCs) with a switched-capacitor front end is an important first step in understanding how to design an interface to these types of pipeline ADCs. The characteristic input impedance that the ADC exhibits must be determined before designing any high frequency interface, regardless of whether it is active, passive, dc-coupled, or ac-coupled.

This application note develops a method, using measurements made with a network analyzer, to provide a better understanding of the input response over high frequency ranges. This allows users to design a more effective interface to unbuffered converters with switched-capacitor inputs. All measurements and model calculations were made using the AD9236 in a 32-lead chip scale package (CSP).

The converter's internal sample-and-hold amplifier circuit (SHA) is mainly comprised of an input switch, an input sampling capacitor, a sampling switch, and an amplifier. As Figure 1 shows, the input switch interfaces the driver circuit with the input capacitor. When the input switch is on (track mode), the driver circuit drives the input capacitor. The input is sampled (captured) on the input capacitor at the end of this mode. When the input switch is off (hold mode), the driver is isolated from the input capacitor. The track mode period and the hold mode period of the converter are approximately equal.

The interface problem with an unbuffered (switched-capacitor) converter is seen as two fold—the frequency domain response, which this application note presents, and time domain response. The first issue is that the input impedance during the track mode of the SHA is different from the input impedance during the hold mode of the SHA. This makes it difficult to accurately impedance match the converter's input with the front-end circuit for high IF designs. Since the converter samples at the input signal only during the track mode, the input impedance

should be matched for this mode. The frequency dependence of the input impedance is governed mainly by the sampling capacitor and any parasitic capacitance in the signal path. For accurate impedance matching, it is helpful to have an idea of the frequency dependence of the input impedance. The measurement results obtained from the AD9236 explain the behavior of the input impedance over a wide range of input frequencies. The Example section of this application note then shows a way to determine an input interface with the converter during the track mode.

The second problem lies in the time domain where the internal switched-capacitor front end presents “kickback” into the driver circuit. This problem occurs when the converter switches from one mode to the other, charging the input capacitors from the previous sample to the current sample. Therefore, the current glitch occurring at the input of the converter is dependent on three factors—the difference between the previous and the current samples, the value of the input sampling capacitor, and the sum of all resistances in the signal path (this is comprised of the on resistance of the switches in the signal path and any series resistance in the signal path).

A time domain example of a current glitch seen at the analog input pin is shown in Figure 2 and Figure 3. Figure 4 shows the frequency domain content of the current glitch of the entire network, in this case, on the primary side of a transformer-coupled network.

If the nonlinear portion of the current glitch corrupts the input sample when the driver has a linear response, the resulting sampled signal will distort. Therefore, it is crucial to design an input network (that is, a transformer or amplifier driver) capable of settling the current glitch within a half-clock cycle to preserve the converter's performance.

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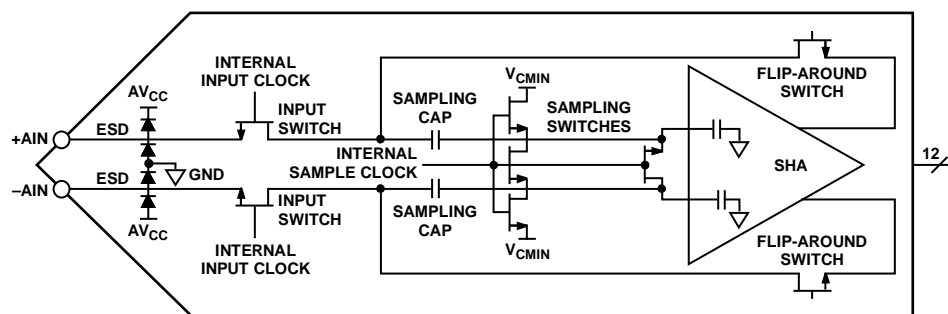


Figure 1. Unbuffered Converter Input Front-End Model

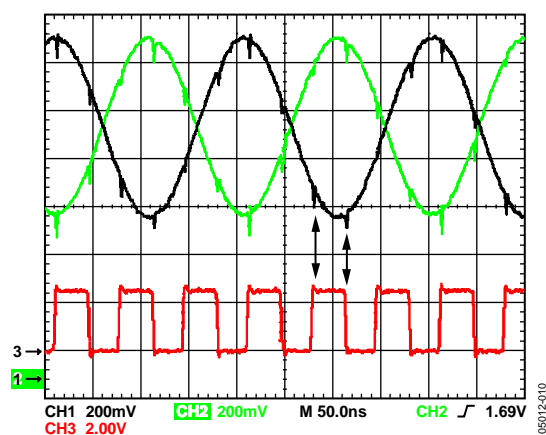


Figure 2. Single-Ended (+AIN or -AIN) Time Domain Measurement at the Analog Input Pins

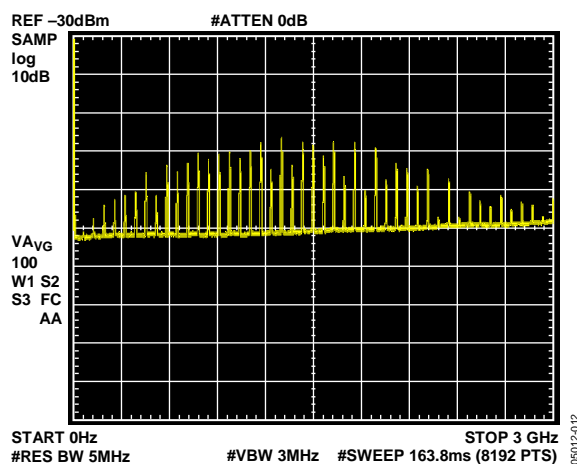


Figure 4. Frequency Domain Measurement of the Entire Network

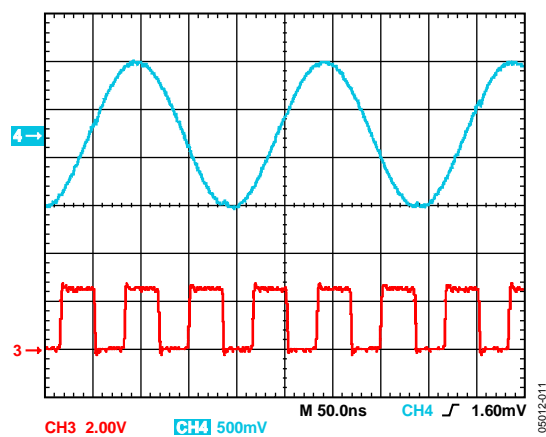


Figure 3. Differential (+AIN or -AIN) Time Domain Measurement at the Analog Input Pins

## METHOD

To understand the converter's frequency response, the internal front end of an AD9236 was measured accurately using a network analyzer. A special AD9236 evaluation board was redesigned to keep the input traces short and to minimize as many board parasitics as possible. The evaluation board was biased at nominal supply voltages and clocked at 1 MSPS.

Figure 5a shows the timing setup used to ensure that the network analyzer sampled during the track mode. The duty cycle of the clock was set to 90% to provide leeway for the converter's input settling and the network analyzer capture delays. The same setup was used to take measurements during the hold mode, except that the clock was inverted, as shown in Figure 5b.

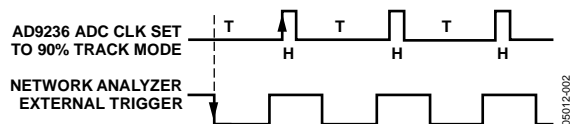


Figure 5a. Timing Diagram Setup—Track Mode

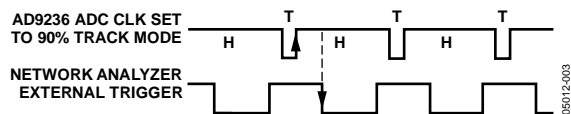


Figure 5b. Timing Diagram Setup—Hold Mode

The measurement setup is shown in Figure 6. The network analyzer was configured to capture 1,601 points over a 300 kHz to 1 GHz frequency range. A 2-channel pulse generator with matched cables was used to strobe the evaluation board and external trigger of the network analyzer at the same time. Power supplies were applied to properly bias the converter and provide a common-mode voltage of +1.5 V ( $AVDD/2$ ) to each analog input.

Measurements were made on the evaluation board, and also on an error board, which is a portion of the evaluation board containing the same trace parasitics seen by the ac-coupling capacitor, and two common-mode resistor dividers that develop the common-mode voltage on the analog inputs. The error board data is used to de-embed the errors caused from these sources, allowing the ADC's input structure to be measured independently (see Equation 1).

$$\text{Evaluation Board (parasitics + AD9236)} - \text{Error Board (parasitics)} = \text{Evaluation Board (AD9236)} \quad (1)$$

## MEASUREMENTS

The measurements taken are in single-ended form. Due to the network analyzer's limited capabilities, however, a popular method of converting these measurements from single-ended to differential was used. The following equation converts a single-ended measurement to differential by using the LogMag scattering parameters (S-parameters) S11, S12, S21, and S22 from the network analyzer.

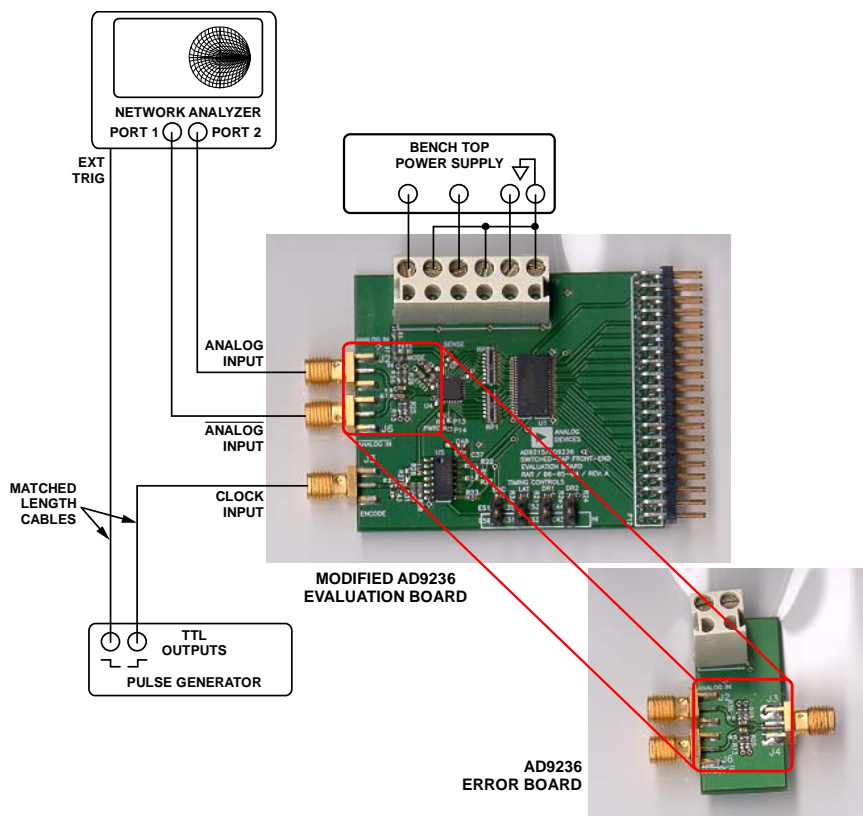


Figure 6. Converter Input Impedance Measurement Setup

$$\Gamma_s = \frac{(2 \times S11 - S21)(1 - S22 - S12) + (1 - S11 - S21)(1 + S22 - 2 \times S12)}{(2 - S21)(1 - S22 - S12) + (1 - S11 - S21)(1 + S22)} \quad (2)$$

A differential impedance,  $Z_{DIFF}$ , can be derived by taking Equation 2 a step further, as shown in Equation 3. This produces the equivalent parallel real and imaginary impedance ( $Z_{DIFF}$ ) circuit from the series type measurement.

$$Z_{DIFF} = 50 \times [(1 + \tau)/(1 - \tau)] = R \pm jX \quad (3)$$

Using the advanced design system (ADS) software simulation package from Agilent Technologies, data was exported from the network analyzer, converted to differential, and the common-mode component error was subtracted out (see Figure 8).

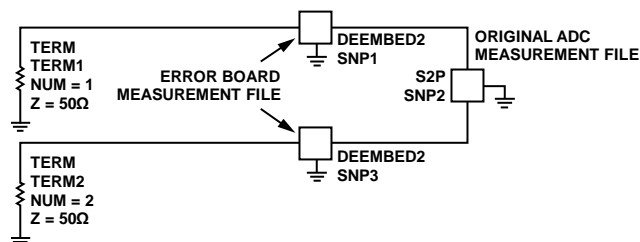


Figure 7. ADS Configuration Setup

## RESULTS

The result of these computations shows real and imaginary components in both track and hold modes. The values that represent the real part in ohms are located on the left side of Figure 8. The values that represent the imaginary or capacitive part in pF are located on the right side of Figure 8.

In track mode (at low frequencies), the real part looks like a very high impedance, settling to roughly 700 Ω at 200 MHz. Referring back to the converter input model of Figure 1, the input impedance is approximately equal to the resistive equivalent of the series parallel combination of transistors in the track mode. The imaginary part starts at 4 pF at 200 MHz, rolling off to 1.5 pF at 1 GHz. These values are to be expected because the input stage during the track mode is the sum of the series parallel combination of the transistors' parasitic capacitance. In hold mode, the real part of the impedance is much higher, dropping to roughly 570 Ω at 1 GHz. The

imaginary part, however, quickly falls to 1 pF or less throughout the entire measurement range, as was expected for the ESD and package parasitics. This is due to the input structure looking essentially like an open circuit (as shown in Figure 1).

Figure 9 shows an expanded view of Figure 8 that depicts the usable impedance matching range.

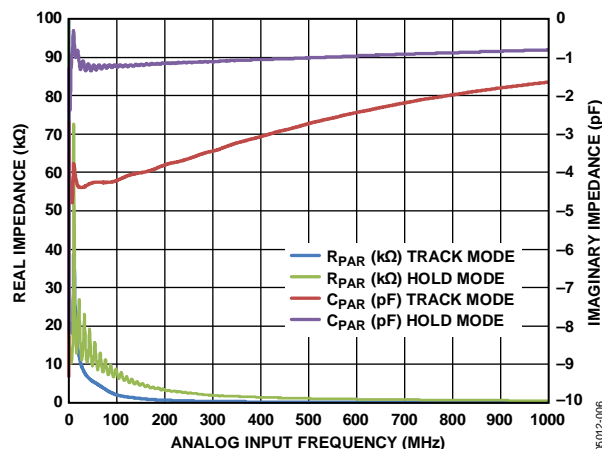


Figure 8. Differential Input Impedance vs. Analog Input Frequency

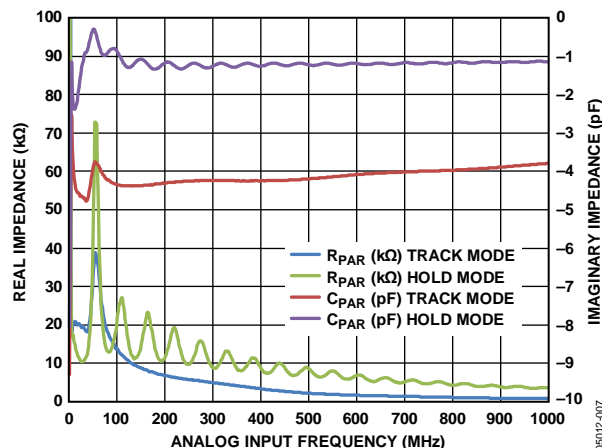


Figure 9. Differential Input Impedance vs. Analog Input Frequency (Expanded)

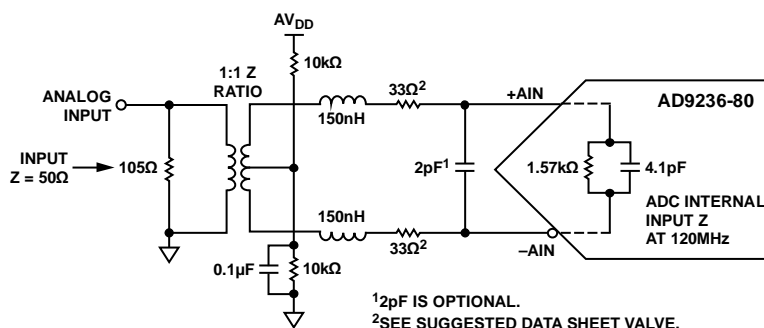


Figure 10. Impedance Matching Example

## EXAMPLE

This section provides an example of how to interface with the AD9236 using a transformer-coupled input based on the measured results. With an analog input frequency at 120 MHz, the AD9236 looks like a 1.57 k $\Omega$  differential resistor and 4.1 pF capacitor during the track mode. If the input impedance is designed to 50  $\Omega$ , then one implementation could be represented as shown in Figure 10.

Other advantages gained from using this circuit topology when designing interface circuits for switch-capacitor ADCs include keeping distortion products low by having a matched differential input termination, as well as high common-mode rejection from switching transients (note the two 33  $\Omega$  series resistors). In addition, a capacitor value could be determined based on the amount of bandwidth wanted for your particular application. For this example a 2 pF was chosen to reduce any wideband aliasing noise seen by the converter.

The key is to make the input look as real as possible when designing at high intermediate frequencies (IFs). Since the input is capacitively dominated, the goal is to find a matching inductive term in order to cancel the imaginary impedance. The math involved to complete this operation using complex terms is as follows:

$$X_{C1} = \frac{1}{2\pi 120M 4.1p} = -j323\Omega, X_{C2} = \frac{1}{2\pi 120M 2p} = -j663\Omega$$

$$(1.57k - j0) \parallel (0 - j323\Omega) = (64 - j310)\Omega$$

$$(64 - j310) \parallel (0 + j663) = (29.5 - j213.33)\Omega$$

Set  $X_L = 213\Omega$  and solve for L at 120 MHz; this equals 283 nH.

Now that L has been found, divide it equally and place it in series with the 33  $\Omega$  resistors on the secondary of the transformer as shown in Figure 10. Note that the 33  $\Omega$  value may depend on the converter being used for the design. For the best spurious performance, see the suggested values in the product data sheet.

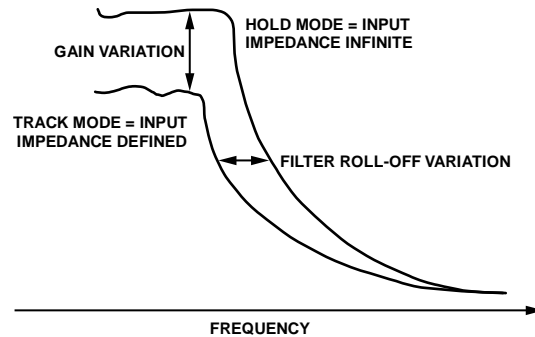
Add all of the components together to find the resulting impedance seen at the secondary of the transformer. Remember, the L is added in, canceling out the capacitive term and making the input look mostly real.

$$(29.5 - j213.33) + (66 + j213.33) = 95.5\Omega$$

The transformer has a 1:1 impedance ratio, therefore 95  $\Omega$  is the impedance seen at the primary of the transformer in parallel with the 105  $\Omega$  resistor. These two resistors in parallel further yield the 50  $\Omega$  termination,  $95 \parallel 105 = 50\Omega$ .

With the converter input S-parameters at hand, a better expectation of the preceding filter or amplifier's load termination can be defined as this example shows. This allows the designer to minimize the load mismatches, which result in gain and roll-off variations in the pass band. Ultimately, it is these types of variations that can cause noise and distortion degrading the converter's expected performance.

An exaggerated example of a particular filter response is shown in Figure 11. Note that the frequency response of the filter changes as the load termination changes. This simple illustration gives the designer a feel for what to expect when designing the front-end interface without further compensation.



### NOTES

1. THE SAME CHARACTERISTIC VARIATIONS WILL APPLY TO BOTH SIDES IF USING A BAND-PASS FILTER.

Figure 11. Illustrated Filter Response Due to Load Variation

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## CONCLUSION

This application note hopes to provide some background on internal front ends of unbuffered, switched-capacitor, pipeline converters. A method of measuring the varying input impedance of the track-and-hold circuit is also shown as well as an example of how to resolve an input interface when using this type of converter at high IF frequencies (>70 MHz). Remember to match the impedance for the front-end design in the track mode and design for the center IF frequency band.

When using the converter at 70 MHz and below (baseband), a simple low-pass filter should be adequate. Matching the front-end interface will not be as critical at lower frequencies to achieve optimal performance when using an unbuffered converter.

The data and example presented here is specific to the AD9236 in a CSP package, describing the general behavior of this switched-capacitor ADC family. Other unbuffered, switched-capacitor parts also include the AD9204/AD9212/AD9215/AD9219/AD9222/AD9228/AD9233/AD9235/AD9236/AD9237/AD9238/AD9244/AD9245/AD9246/AD9248/AD9251/AD9252/AD9258/AD9268/AD9287.

## CONVERTER S-PARAMETERS

S-parameter data is available at [www.analog.com](http://www.analog.com). Go to a product page, such as the AD9236 product page, to download the spreadsheet that contains both the real and imaginary data values in both series and parallel. These values are in tabular format and plotted against frequency.

Future products will also be listed on the Analog Devices company website, even though not listed above. Check the Analog Devices website for future postings and product releases on other switched-capacitor ADC families.

## REFERENCES

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**NOTES**