Input Impedance Measurement Using ADC FFT Data

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ABSTRACT

Texas Instruments has introduced a family of high-speed analog-to-digital converters (ADCs) suited to meet the demand for high-speed and high-IF sampling systems. To achieve the highest overall system performance, an analog front-end circuit with an antialiasing filter must drive the ADC with the highest possible dynamic range and lowest distortions. One important parameter of the front-end circuit design is knowing the overall input impedance of the ADC. One method of accurately measuring the ADC input impedance is to use ADC FFT readings to calculate the input impedance that corresponds to the source resistance changes. This application report shows the steps to quickly measure the ADC input impedance and printed circuit board (PCB) parasitics without making additional changes to the test setup and variables such as probe impedance.

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1   Introduction

High-speed ADCs have a track-and-hold (T/H or T&H) stage circuit to sample the input signal in order for the later stages of the ADC to quantize the sampled signal for a discrete time signal. TI has recently introduced a family of ADCs suited to meet the demand for high-speed and high-IF sampling systems. TI also offers ADCs with an integrated buffer before the T/H circuit to provide isolation from the non-linear impedance and the switching transients of the T/H circuit. To achieve the highest overall system performance, the ADC must be driven correctly. The input of the ADC can generally be modeled as a parallel combination of R and C, as shown in Figure 1.
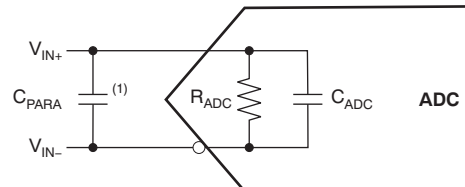
Equivalent input impedance of ADC $= R || (jX)$

where
$R = R_{ADC}$
$jX_{PARA} = jX_{ADC} + jX_{PARA}$

Note: (1): C_{PARA} = PCB parasitic capacitance.

Figure 1. Typical ADC Input Impedance Model

Even though TI provides ADC input impedance values, analog front-end designers often must consider the parasitic capacitance and resistance values associated with the PCB. As a result of the reactive ADC components, measuring the input impedance of the ADC requires both magnitude and phase information. Such measurements may also require multiple instruments and probes that may introduce additional parasitic capacitances and resistances. Figure 2 illustrates an example of this effect.
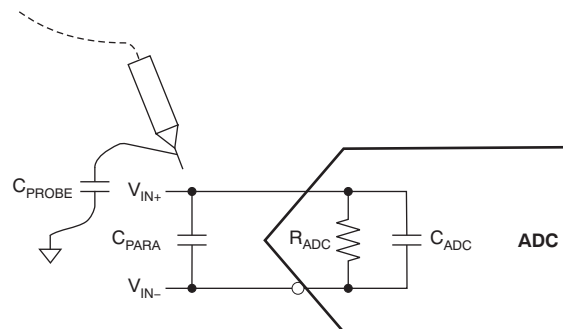

**Figure 2. Probe Capacitance Introduced by Probe**

Additionally, it is often necessary to modify the PCB in order to make the measurement. This modification, in turn, may introduce yet more variables to the actual board impedance.

There is, however, another method to measure the ADC input impedance: compare the fundamental tone power with various input source resistances and fundamental frequencies. With this approach, it is not necessary to have additional equipment or to make board modifications, ultimately saving measurement time and improving measurement accuracy.

2   Measurement Concept

Figure 3 illustrates the measurement concept, which is based on the simple impedance divider theory. If the source resistance of the ADC (R_{Sx}) changes in value, then the magnitude of the ADC input (V_{IN}) also changes. Therefore, the V_{IN} magnitude change is a function of R_{Sx} and the ADC input impedance. If the value of R_{Sx} is known and the delta in V_{IN} magnitude is measured, then the ADC input impedance can be solved.

The advantage of this measurement technique is that the measurement result is independent of the analog network response before R_{Sx} if the change in R_{Sx} value does not affect the analog network response. In other words, if R_{Sx} does not change the signal behavior at the earlier stages, then the measurement result is a function of R_{Sx} and the ADC input impedance only.
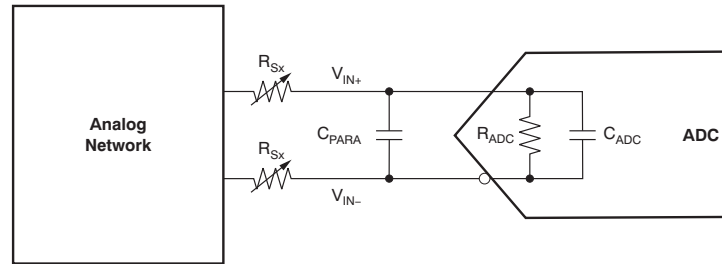
Note: C_{PARA} = PCB parasitic capacitance.

Figure 3. Measurement Concept

Most TI ADCs have inputs that are differential in nature. To simplify the derivation process used in our recommended approach, the input circuit is analyzed in single-ended configuration. As shown in Figure 4, the R_{Sx} value in a single-ended analysis can be set to two times the actual R_{Sx} value used. By doing so, the R and C values remain differential.
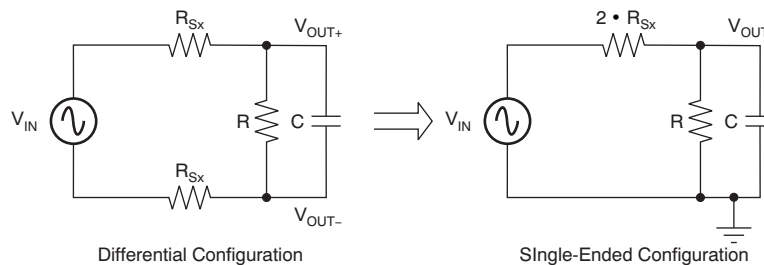

Figure 4. Differential to Single-Ended Transformation

As Figure 5 illustrates, the experiment begins by setting the correct voltage source. To achieve the highest dynamic range with the proper input voltage range, set the signal source amplitude such that the ADC reading of the fundamental tone is at −1 dBFS. Typically, the voltage source may be a signal generator, a differential amplifier, or a transformer network. Small damping resistors of 5 Ω to 15 Ω should be added in series between the signal source and the ADC when setting the reference amplitude. These damping resistors (labeled R_{S0}) can damp out ringing caused by the ADC input package parasitic. Additional information about driving high-speed ADCs may be found in application note SLAA416, available for download at www.ti.com.
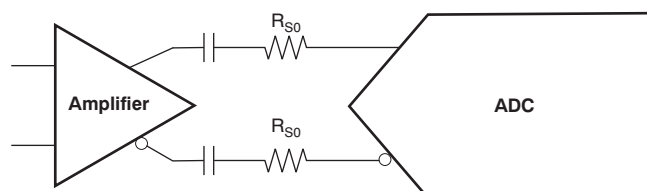

Figure 5. Damping Resistors R_{S0} for Setting Reference Voltage

Figure 6 shows two input circuits with different source resistances, R_{S1} and R_{S2}, respectively. With the reference set at –1 dBFS, the source resistances for the measurements R_{S1} and R_{S2} can now be chosen. These values must be higher than the output impedance of the generator to minimize the amount of errors. For example, to keep the source voltage drop to less than 1%, R_{Sx} must be 100 times greater than the output impedance of the generator. In the following example, $R_{S1} = 100\ \Omega$ and $R_{S2} = 200\ \Omega$ are used for the measurements. If the generator output impedance is significant when compared to R_{Sx}, a later calculation step can account for it. The source frequency, f_1, is set to be the center frequency of interest, and it is the fundamental tone measured in the FFT plot.
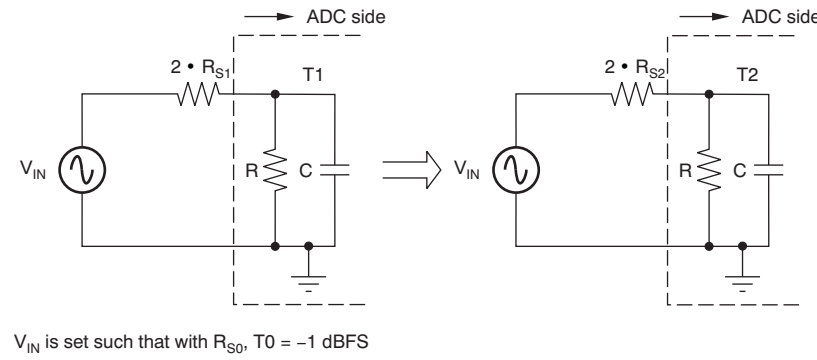

V_{IN} is set such that with R_{S0}, T0 = –1 dBFS

Figure 6. ADC FFT Measurements with R_{S1} and R_{S2}

Figure 7 shows several diagrams of such measurements.

Measurement #1 with R_{S1}
(FFT Plot for T1 and FFT Plot for T3 are overlapped)

Measurement #2 with R_{S2}
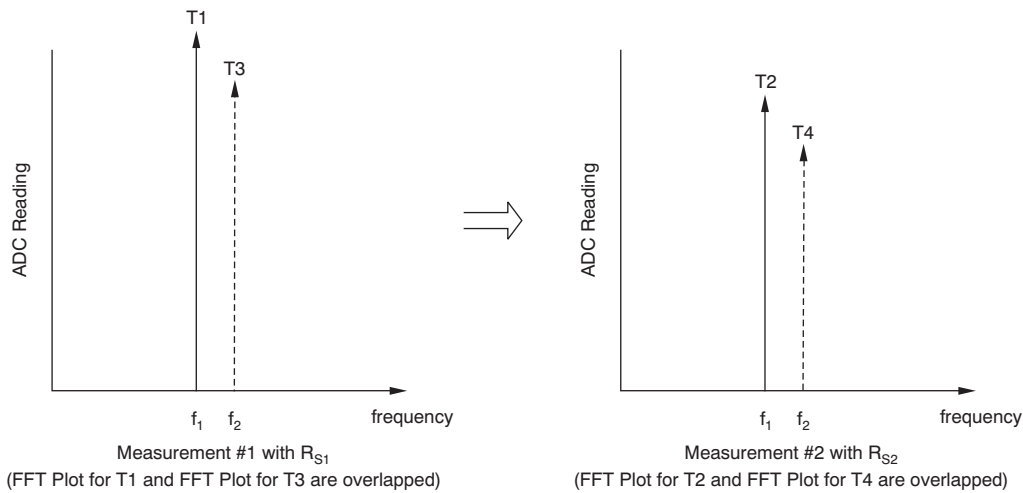(FFT Plot for T2 and FFT Plot for T4 are overlapped)

Figure 7. ADC FFT Measurement Results (f_1 and f_2 Spectrum Overlapped)

T1 is the fundamental power measured in the ADC FFT reading at f_1 with source resistance R_{S1}, and T2 is the FFT fundamental power at f_1 measured with the source resistance R_{S2}. The value of T1 and T2 will differ because the known source resistances (R_{S1} and R_{S2}) changed. Therefore, the ratio between T1 and T2, defined as $M(f_1)$, is a function of $f(R_{S1}, R_{S2}, R, C)$. Both R_{S1} and R_{S2} are known; therefore, $M(f_1)$ is only a function of R and X. Thus, $M(f_1)$ is a function of $f(R, C)$. Equation 1 gives the definition of $M(f)$ with respect to R and X.

$$\frac{T1}{T2} \equiv M(f_1) = f(R, jX)$$

$$\frac{T3}{T4} \equiv M(f_2) = f(R, jX\frac{f_1}{f_2})$$

(1)

The primary interest here is to solve for two variables, R and C. This process requires a system of equations with two solutions. The system of equations requires another solution besides $M(f_1)$ in order to solve for R and C. The fact that the reactance $jX = 1/(j2\pi f_C)$ changes with frequency allows another measurement to be made in order to obtain the second solution. Thus, if the reactance at f_1 is jX, then the reactance at f_2 will be $jX \cdot f_1 / f_2$, which is proportional to the frequency ratio $f_R = f_1/f_2$. Thus, by taking another set of measurements at f_2, we can obtain $M(f_2)$ by acquiring the FFT fundamental power of T3 and T4, where T3 is the f_2 power when $R_{Sx} = R_{S1}$, and T4 is the f_2 power when $R_{Sx} = R_{S2}$. With two equations and two unknowns, we can now solve for both R and C.

The frequency f_2 can be chosen within the signal bandwidth of the system. It should also create enough reactance variation for accurate impedance measurement. Typically, ADCs with buffered input before the T&H circuit are designed for flat input impedance with respect to input frequency. The selection of f_2 should have minimal impact on the impedance measurement.

Special attention is needed for ADCs without a buffered input because the input impedance does change with respect to input frequency. There are trade-offs for the selection of f_2: f_2 cannot be too far away from f_1 because the impedance variation with frequency can create errors, and f_2 must be far enough away to create enough impedance variation. The product data sheet shows a typical impedance versus frequency performance curve, and it helps the user to make the initial f_1 and f_2 selections.

3   Derivation

The next step is to find an equation for M(f) in terms of R and X in order to solve for R and C. Again, the R_{Sx} value is set to be two times the actual R_{Sx} value, so that the R and C values remain differential.
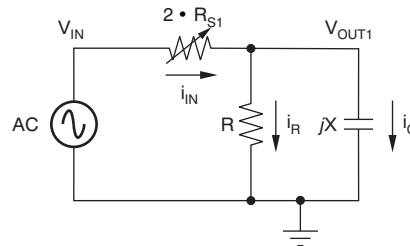

Figure 8. KCL at ADC Input

First, as Figure 8 shows, write the KCL equation at node V_{OUT1}. The ADC reading T1 is proportional to V_{OUT1}, so T1 is also proportional to the transfer function. Equation 2 shows the derivation of the transfer function.

$$i_{IN} = i_R + i_C$$

$$\frac{V_{IN} - V_{OUT1}}{2R_{S1}} = V_{OUT1} \bullet \left(\frac{1}{R} + \frac{1}{jX} \right)$$

$$V_{IN} = V_{OUT1} \bullet \left(1 + \frac{2R_{S1}}{R} - j\frac{2R_{S1}}{X} \right)$$

$$T1 \propto \frac{V_{OUT1}}{V_{IN}} = \frac{1}{1 + \dfrac{2R_{S1}}{R} - j\dfrac{2R_{S1}}{X}}$$

(2)

This measurement is a ratio measurement: two measurements with two different source resistances are required to form $M(f_1)$. The transfer function is a complex function that contains both magnitude and phase information. However, because all the measurements taken from the FFT contain only the magnitude information, the function $M(f_1)$ must be the magnitude of the ratio between the two transfer functions. Equation 3 shows $M(f_1)$ as a function of T1 and T2.

$$T1 \propto \frac{V_{OUT1}}{V_{IN}} = \frac{1}{1 + \dfrac{2R_{S1}}{R} - j\dfrac{2R_{S1}}{X}}$$

$$T2 \propto \frac{V_{OUT2}}{V_{IN}} = \frac{1}{1 + \dfrac{2R_{S2}}{R} - j\dfrac{2R_{S2}}{X}}$$

$$M(f_1) = \left|\frac{T1}{T2}\right|^2 = \left| \frac{1 + \dfrac{2R_{S2}}{R} - j\dfrac{2R_{S2}}{X}}{1 + \dfrac{2R_{S1}}{R} - j\dfrac{2R_{S1}}{X}} \right|^2$$

(3)

Another function, $M(f_2)$, based on frequency f_2 is required to solve the two variables. Based on the concept discussed in the Measurement Concept section, Equation 4 shows $M(f_2)$ as a function of T3 and T4.

$$M(f_2) = \left|\frac{T3}{T4}\right|^2 = \left| \frac{1 + \dfrac{2R_{S2}}{R} - j\dfrac{2R_{S2}}{X/f_R}}{1 + \dfrac{2R_{S1}}{R} - j\dfrac{2R_{S1}}{X/f_R}} \right|^2 \qquad \text{where } f_R = \frac{f_2}{f_1}$$

(4)

The expansion of M(f) results in a multi-order equation and is very difficult to solve by hand. We used the computer solver MathCAD™ [1] to expand M(f); this expansion is shown as Equation 5.

$$M(f_1) = \frac{\left[\dfrac{2R_{S2}}{R} + \dfrac{4R_{S1}\bullet R_{S2}}{R^2} + \dfrac{2R_{S1}}{R} + \dfrac{4R_{S1}\bullet R_{S2}}{X^2} + 1 \right]^2 + \left[\dfrac{2R_{S1} - 2R_{S2}}{X} \right]^2}{\left[\left(1 + \dfrac{2R_{S1}}{R}\right)^2 + \left(\dfrac{2R_{S1}}{X}\right)^2 \right]^2}$$

$$M(f_2) = \frac{\left[\dfrac{2R_{S2}}{R} + \dfrac{4R_{S1}\bullet R_{S2}}{R^2} + \dfrac{2R_{S1}}{R} + \dfrac{4R_{S1}\bullet R_{S2}}{(X/f_R)^2} + 1 \right]^2 + \left[\dfrac{2R_{S1} - 2R_{S2}}{(X/f_R)} \right]^2}{\left[\left(1 + \dfrac{2R_{S1}}{R}\right)^2 + \left(\dfrac{2R_{S1}}{X/f_R}\right)^2 \right]^2} \qquad \text{where } f_R = \frac{f_2}{f_1}$$

(5)

[1]   See the attached MathCAD file available as a zipped file download for an example.

4   Experiment

As a demonstration, the following experiment measured the input impedance of the ADS5493 on an evaluation module (EVM) board. As shown in Figure 9, the test setup consisted of two HP8644B source generators (one source for the clock and one source for the analog input), a TSW1200 High-Speed ADC capture card, and power supplies to power the EVMs.

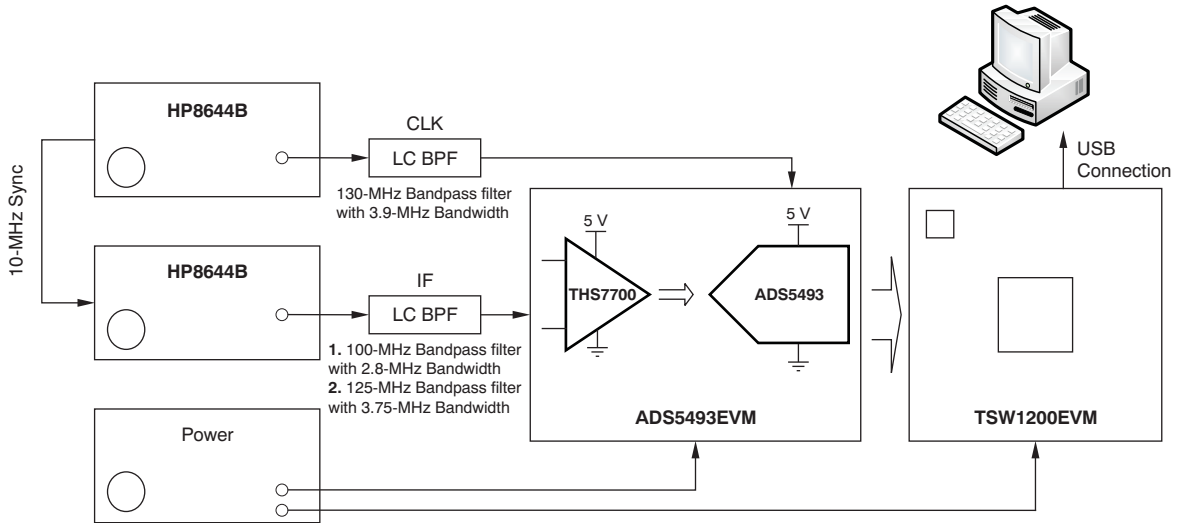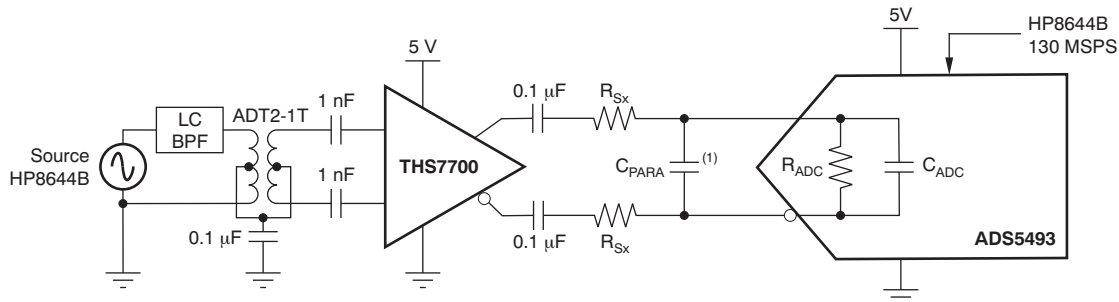**Figure 9. Test Setup**

The ADS5493 is a 16-bit, 130-MSPS input-buffered ADC. The ADS5493EVM contains a THS7700 high-speed, fully-differential op amp to drive the ADC. Figure 10 shows the analog front-end of the ADC:

(1) C_{PARA} = PCB parasitic capacitance.

Figure 10. ADS5493 EVM Setup

The LC bandpass filter (BPF in the illustration) with a center frequency f_C of either f_1 or f_2 goes between the generator and the transformer to limit the amount of noise and spurs that go into the ADC. The ADT2-1T transformer is used to transform the single-ended signal into a differential signal for the later stages. The 0.1-µF ac-coupling capacitors at the output of the THS7700 isolate the dc common-mode voltage difference between the amplifier and the ADC, which are 2.5 V and 3.15 V, respectively. The THS7700 also has a very low output resistance that is negligible for the later calculations. However, if the generator used in the setup has a high output impedance, the output impedance value must be added to the source resistance value R_{Sx} during the calculation, as shown in Figure 11. The source resistances R_{Sx} will be changed throughout the measurement to generate a different fundamental tone power.

Where $R_{S\_Calc} = R_{GEN} + 2 \cdot R_{SX}$
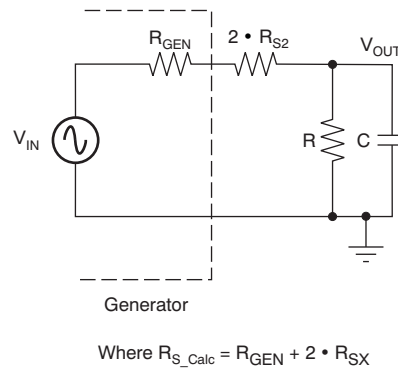
Note: R_{S_Calc} will account for generator output impedance.

Figure 11. Effect of Generator Output Impedance

The source power is set such that when $R_{S0} = 10\ \Omega$, the ADS5493 reads –1 dBFS. This power may differ between f_1 and f_2 as a result of the different insertion loss of the LC bandpass filters.

Figure 12 shows two sets of measurements that were done on two sets of resistor values: $R_{S1} = 100\ \Omega$ and $R_{S2} = 200\ \Omega$. The fundamental power at f_1, T1 and T2, and the fundamental power at f_2, T3 and T4, are the measurements needed to form the values of $M(f_1)$ and $M(f_2)$. $M(f_1)$ and $M(f_2)$ can be calculated using Equation 6. The two frequencies used in this experiment are 100 MHz and 125 MHz. From the derivations above, the values of $M(f_1)$ and $M(f_2)$ will determine the R and C value of the ADC.

Generator Information		Filter Information						
HP8644B		Trilithic 4BE100/X3-3kk						
Power = 2.1dBm		Filter Fc = 100MHz						
Frequency = 100MHz		Filter BW = 2.6MHz						
M(f1) Measurement Data						**M(f1) Measurement Result**		
Trial	1 (dBFS)	2 (dBFS)	3 (dBFS)	average			(dB)	(ratio)
T0	-0.970	-0.960	-0.950	-0.960		M(f1)	1.433	1.391
T1	-2.130	-2.130	-2.130	-2.130				
T2	-3.550	-3.570	-3.570	-3.563				
Generator Information		Filter Information						
HP8644B		TTE KC4T-125M-3p-50-69a						
Power = 4.6dBm		Filter Fc = 125M						
Frequency = 125MHz		Fitler BW = 3.75MHz						
M(f2) Measurement Data						**M(f2) Measurement Result**		
Trial	1 (dBFS)	2 (dBFS)	3 (dBFS)	average			(dB)	(ratio)
T0	-1.010	-1.010	-1.010	-1.010		M(f2)	1.740	1.493
T3	-2.340	-2.340	-2.340	-2.340				
T4	-4.080	-4.080	-4.080	-4.080				

Figure 12. FFT Data from the Measurements

$M(f_1)$ dB = T1 – T2
$M(f_1)$ ratio = $10^{[M(f_1)\ dB/10]}$

$M(f_2)$ dB = T3 – T4
$M(f_2)$ ratio = $10^{[M(f_2)\ dB/10]}$

(6)

There are three trials for each FFT power measurements so the measurements can be averaged in order to minimize variations. The average values of T1, T2, T3, and T4 generated $M(f_1)$ and $M(f_2)$, and the system of equations use $M(f_1)$ and $M(f_2)$ to solve the R and X variables. Again, using computer math solver MathCAD to solve R and X, the result is shown in Equation 7.

$$M(f_1) = \frac{\left[\frac{2R_{S2}}{R} + \frac{4R_{S1} \cdot R_{S2}}{R^2} + \frac{2R_{S1}}{R} + \frac{4R_{S1} \cdot R_{S2}}{X^2} + 1\right]^2 + \left[\frac{2R_{S1} - 2R_{S2}}{X}\right]^2}{\left[\left(1 + \frac{2R_{S1}}{R}\right)^2 + \left(\frac{2R_{S1}}{X}\right)^2\right]^2}$$

$$M(f_2) = \frac{\left[\frac{2R_{S2}}{R} + \frac{4R_{S1} \cdot R_{S2}}{R^2} + \frac{2R_{S1}}{R} + \frac{4R_{S1} \cdot R_{S2}}{(X/f_R)^2} + 1\right]^2 + \left[\frac{2R_{S1} - 2R_{S2}}{(X/f_R)}\right]^2}{\left[\left(1 + \frac{2R_{S1}}{R}\right)^2 + \left(\frac{2R_{S1}}{X/f_R}\right)^2\right]^2}$$

$$\text{solve:} \left(\frac{R}{X}\right) \rightarrow \begin{pmatrix} 2026.1427161082670125 & -652.33949955217548931 \\ 2026.1427161082670125 & 652.33949955217548931 \\ -295.70103763163318988 & -2214.5875215554317604 \\ -295.70103763163318988 & 2214.5875215554317604 \end{pmatrix}$$

(7)

Because the solution cannot be negative, only one solution is valid: R = 2026 and X = 652. Equation 8 can solve for capacitance based on the X value. This solution translates to about 2.44 pF of differential capacitance and 2 kΩ of differential resistance between A_{IN+} and A_{IN-}.

$$R = 2026 \ \Omega$$

$$X = 652 \ \Omega$$

$$C_{DIFF} = \frac{1}{2 \cdot \pi \cdot X \cdot f_1}$$

$$C_{DIFF} = 2.441 \ pF$$

(8)

To verify the measurement result, refer to the ADS5493 product data sheet for the typical input impedance values. The specified analog inputs, shown in Table 1, list the resistance R and capacitance C.

Table 1. ADS5493 Data Sheet: Analog Inputs Specification

PARAMETER		TEST CONDITIONS	ADS5493			UNIT
			MIN	TYP	MAX	
ANALOG INPUTS						
	Differential input range	Programmable from 1.5 V_{PP} to 2.5 V_{PP}			2.5	V_{PP}
VCM	Analog input common-mode voltage	Self-biased to AVDD5 / 2 + diode		3.15		V
	Input resistance, differential (dc)			2		kΩ
	Input capacitance	Each input to GND (excluding soldered package), adds typically 1 pf to 2 pF once soldered; board-dependent		3.6		pF
	Analog input bandwidth (–3 dB)			600		MHz

The input differential resistance is listed as 2 kΩ, and the single-ended input capacitance is listed as 3.6 pF when the device is unsoldered. Once the ADS5493 is soldered to the board, the capacitance increases typically by 1 pF to 2 pF depending on the board layout. Therefore, the onboard input capacitance may be between 4.6 pF to 5.6 pF for a single-ended configuration; this result is equivalent to 2.3 pF to 2.8 pF of differential capacitance. The measured differential input impedance value of 2 kΩ and 2.44 pF falls within the specified data sheet range.

Table 2 summarizes the results.

Table 2. Data Sheet Value vs. Measured Results

	Data Sheet	Measured
R (differential)	2 kΩ	2.026 kΩ
C (differential)	2.3 pF to 2.8 pF	2.44 pF

The steps needed for the measurement are summarized below:

Step 1.   Determine the two frequencies f_1 and f_2 to be used in the measurement.

Step 2.   Place R_{S0} resistors. Set the generator power for f_1 and f_2 so that the fundamental power reading at f_1 and f_2 will be –1 dBFS. The actual generator power may vary because of the filter insertion loss.

Step 3.   Place R_{S1} resistors. Set the generator power based on Step 2, and measure T1 and T3 accordingly.

Step 4.   Place R_{S2} resistors. Set the generator power based on Step 2 and measure T2 and T4.

Step 5.   Plug in T1, T2, T3, and T4 data to $M(f_1)$ and $M(f_2)$. Use Equation 5 to determine the values of R and C. Refer to the attached MathCAD file available as a zipped file download for an example.

5   Conclusion

The FFT data of the ADC allows the user to measure the onboard ADC input impedance by taking the fundamental tone power at two different source resistances and two different fundamental tone frequencies. This method eliminates variables introduced by the probe parasitic and board modifications. Moreover, system designers can incorporate the impedance result in an analog front-end or filter design for proper source and load impedance matching. This method may speed up design and test time for the system.

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