ANALOG DEVICES

Circuit Note
CN-0217

Circuits from the Lab™ Reference Circuits

Circuits from the Lab™ reference circuits are engineered and tested for quick and easy system integration to help solve today's analog, mixed-signal, and RF design challenges. For more information and/or support, visit www.analog.com/CN0217.

Devices Connected/Referenced	
AD5933	1 MSPS, 12-Bit Impedance Converter, Network Analyzer
AD5934	250 kSPS, 12-Bit Impedance Converter, Network Analyzer
AD8606	Precision, Low Noise, Dual CMOS Op Amp

High Accuracy Impedance Measurements Using 12-Bit Impedance Converters

EVALUATION AND DESIGN SUPPORT

Circuit Evaluation Boards

AD5933 Evaluation Board (EVAL-AD5933EBZ)

Design and Integration Files

Schematics, Layout Files, Bill of Materials

CIRCUIT FUNCTION AND BENEFITS

The AD5933 and AD5934 are high precision impedance converter system solutions that combine an on-chip programmable frequency generator with a 12-bit, 1 MSPS (AD5933) or 250 kSPS (AD5934) analog-to-digital converter (ADC). The tunable frequency generator allows an external complex impedance to be excited with a known frequency.

The circuit shown in Figure 1 yields accurate impedance measurements extending from the low ohm range to several hundred kΩ, and it also optimizes the overall accuracy of the AD5933/AD5934.

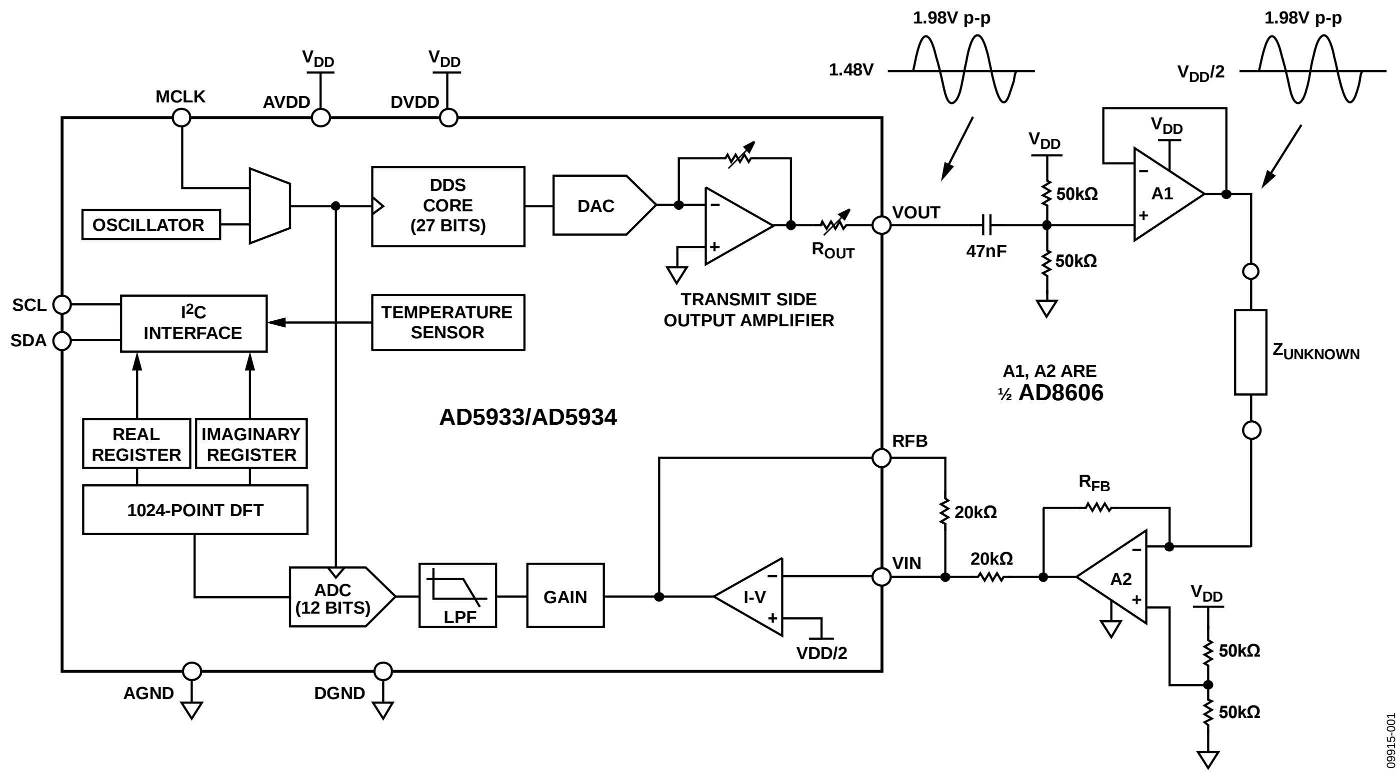

Figure 1. Optimized Signal Chain for Impedance Measurement Accuracy (Simplified Schematic, All Connections and Decoupling Not Shown)

Rev. A

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CIRCUIT DESCRIPTION

The AD5933 and AD5934 have four programmable output voltage ranges; each range has an output impedance associated with it. For example, the output impedance for a 1.98 V p-p output voltage is typically 200 Ω (see Table 1).

Table 1. Output Series Resistance (R_{OUT}) vs. Excitation Range for V_{DD} = 3.3 V Supply Voltage

Range	Output Excitation Amplitude (V p-p)	Output Resistance (R_{OUT})
Range 1	1.98	200 Ω typical
Range 2	0.97	2.4 kΩ typical
Range 3	0.383	1.0 kΩ typical
Range 4	0.198	600 Ω typical

The output impedance affects the impedance measurement accuracy, particularly in the low kΩ range, and must be taken into account when calculating the gain factor. Refer to the AD5933 or AD5934 data sheets for more details on the gain factor calculation.

A simple buffer in the signal chain prevents the output impedance from affecting the unknown impedance measurement. Select a low output impedance amplifier with sufficient bandwidth to accommodate the AD5933/AD5934 excitation frequency. An example of the low output impedance achievable is shown in Figure 2 for the AD8605/AD8606/AD8608 family of CMOS op amps. The output impedance for this amplifier for an A_V of 1 is less than 1 Ω up to 100 kHz, which is the maximum operating range of the AD5933/AD5934.

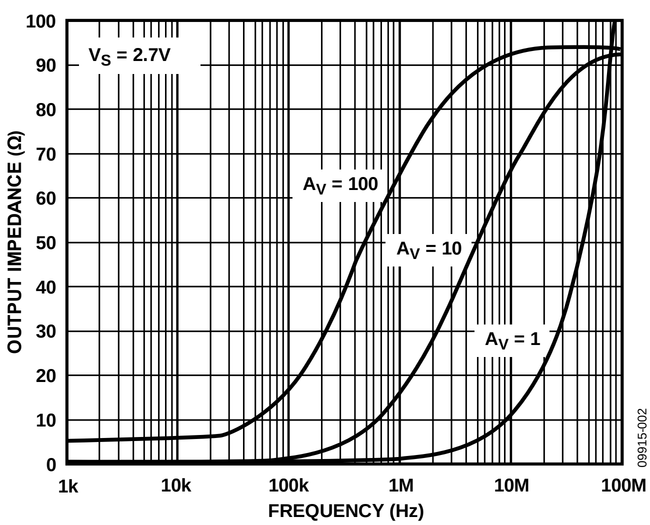

Figure 2. Output Impedance of AD8605/AD8606/AD8608

Matching the DC Bias of Transmit Stage to Receive Stage

The four programmable output voltage ranges in the AD5933/AD5934 have four associated bias voltages (see Table 2). For example, the 1.98 V p-p excitation voltage has a bias of 1.48 V. However, the current-to-voltage (I-V) receive stage of the AD5933/AD5934 is set to a fixed bias of $V_{DD}/2$ as shown in Figure 1. Therefore, for a 3.3 V supply, the transmit bias voltage is 1.48 V, and the receive bias voltage is 3.3 V/2 = 1.65 V. This potential difference polarizes the impedance under test and can cause inaccuracies in the impedance measurement.

One solution is to add a simple high-pass filter with a corner frequency in the low Hz range. Removing the dc bias from the transmit stage and rebiasing the ac signal to $V_{DD}/2$ keeps the dc level constant throughout the signal chain.

Table 2. Output Levels and Respective DC Bias for V_{DD} = 3.3 V Supply Voltage

Range	Output Excitation Amplitude (V p-p)	Output DC Bias Level (V)
1	1.98	1.48
2	0.97	0.76
3	0.383	0.31
4	0.198	0.173

Selecting an Optimized I-V Buffer for the Receive Stage

The I-V amplifier stage of the AD5933/AD5934 can also add minor inaccuracies to the signal chain. The I-V conversion stage is sensitive to the amplifier's bias current, offset voltage, and common-mode rejection ratio (CMRR). By selecting the proper external discrete amplifier to perform the I-V conversion, the user can choose an amplifier with lower bias current and offset voltage specifications along with excellent CMRR, making the I-V conversion more accurate. The internal amplifier can then be configured as a simple inverting gain stage.

Selection of the R_{FB} resistor still depends on the gain through the system as described in the AD5933/AD5934 data sheets.

Optimized Signal Chain for High Accuracy Impedance Measurements

Figure 1 shows a proposed configuration for measuring low impedance sensors. The ac signal is high-pass filtered and rebiased before buffering with a very low output impedance amplifier. The I-V conversion is completed externally before the signal returns to the AD5933/AD5934 receive stage. Key specifications that determine the required buffer are very low output impedance, the single-supply capability, low bias current, low offset voltage, and excellent CMRR performance. Some suggested parts are the ADA4528-1, AD8628, AD8629, AD8605, and AD8606. Depending on board layout, use a single-channel or dual-channel amplifier. Use precision 0.1% resistors for both the biasing resistors (50 kΩ) and gain resistors (20 kΩ and R_{FB}) to reduce inaccuracies.

CIRCUIT EVALUATION AND TEST

The schematic in Figure 1 was developed to improve impedance measurement accuracy, and some example measurements were taken. The AD8606 dual-channel amplifier buffers the signal on the transmit path and converts the receive signal from current to voltage. For the three examples shown, the gain factor is calculated for each frequency increment to remove frequency dependent errors. A complete design package including schematics, bill of materials, layout, and Gerber files is available for this solution at www.analog.com/CN0217-DesignSupport. The software used is the same software that is available with evaluation boards and is accessible from the AD5933 and AD5934 product pages.

Example 1: Low Impedance Range

Table 3. Low Impedance Range Setup for V_{DD} = 3.3 V Supply Voltage

Parameter	Value
Voltage Peak-to-Peak (V p-p)	1.98 V (Range 1)
Number of Settling Time Cycles	15
MCLK	16 MHz
R_{CAL}	20.1 Ω
R_{FB}	20.0 Ω
Excitation Frequency Range	30 kHz to 30.2 kHz
Unknown Impedances	R1 = 10.3 Ω, R2 = 30.0 Ω, C3 = 1 µF (Z_C = 5.3 Ω at 30 kHz)

The results of the low impedance measurements are shown in Figure 3, Figure 4, and Figure 5. Figure 5 is for the 10.3 Ω measurement and is shown on an expanded vertical scale.

The accuracy achieved is very much dependent on how large the unknown impedance range is relative to the calibration resistor, R_{CAL}. Therefore, in this example, the unknown impedance of 10.3 Ω measured 10.13 Ω, an approximate 2% error. Choosing an R_{CAL} closer to the unknown impedance achieves a more accurate measurement; that is, the smaller the unknown impedance range is centered on R_{CAL} is the more accurate the measurement. Consequently, for large unknown impedance ranges, it is possible to switch in various R_{CAL} resistors to break up the unknown impedance range using external switches. The R_{ON} error of the switch is removed by calibration during the R_{CAL} gain factor calculation. Using a switch to select various R_{FB} values can optimize the dynamic range of the signal seen by the ADC.

In addition, note that to achieve a wider range of measurements a 200 mV p-p range was used. If the unknown Z is a small range, a larger output voltage range can be used to optimize the ADC dynamic range.

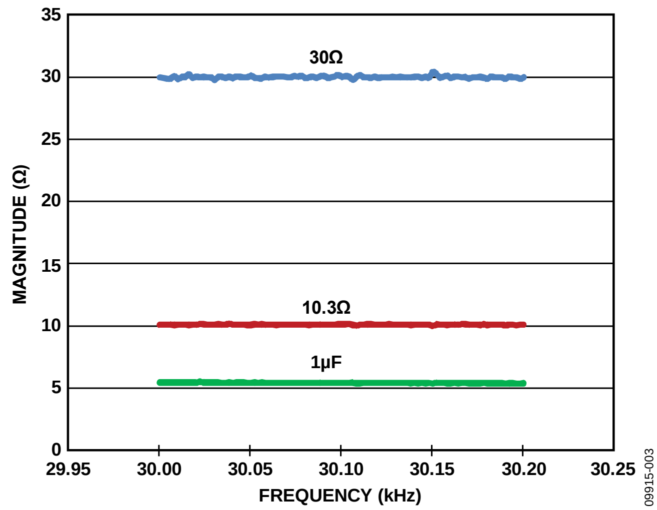

Figure 3. Measured Low Impedance Magnitude Results

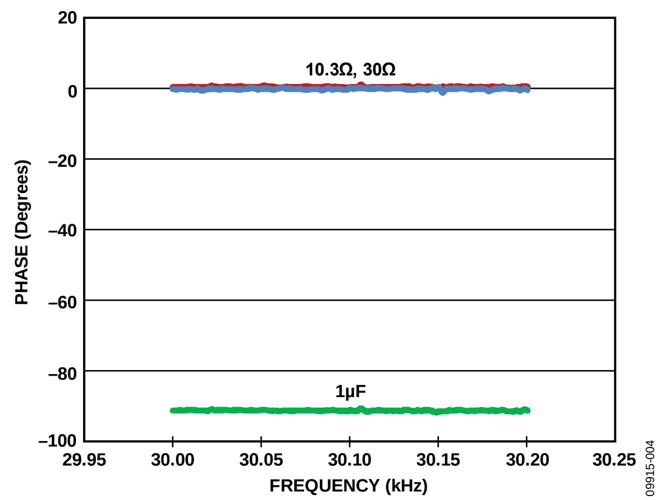

Figure 4. Measured Low Impedance Phase Results

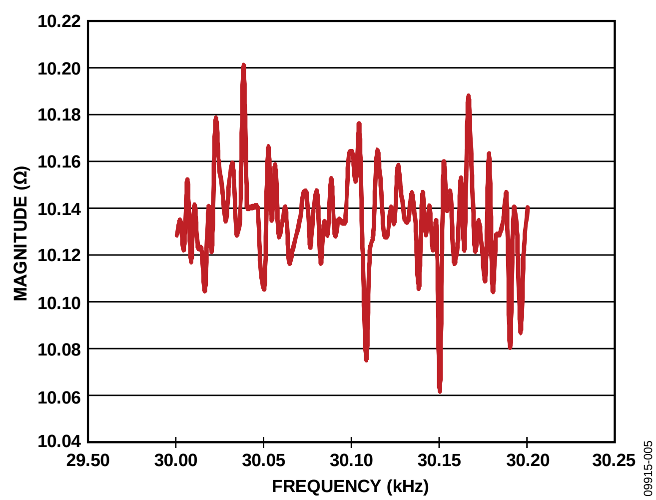

Figure 5. Measured 10.3 Ω Magnitude Results (Expanded Scale)

Example 2: kΩ Impedance Range

Using an R_{CAL} of 99.85 kΩ, a wide range of unknown impedances were measured according to the setup conditions listed in Table 4. Figure 6 to Figure 10 document accuracy results. To improve the overall accuracy, select an R_{CAL} value closer to the unknown impedance. For example, in Figure 9, an R_{CAL} closer to the Z_C value of 217.5 kΩ is required. If the unknown impedance range is large, use more than one R_{CAL} resistor.

Table 4. kΩ Impedance Range Setup for V_{DD} = 3.3 V Supply Voltage

Parameter	Value
Voltage Peak-to-Peak (V p-p)	0.198 V (Range 4)
Number of Settling Time Cycles	15
MCLK	16 MHz
R_{CAL}	99.85 kΩ
R_{FB}	100 kΩ
Excitation Frequency Range	30 kHz to 50 kHz
Unknown Impedances	R0 = 99.85 kΩ, R1 = 29.88 kΩ, R2 = 14.95 kΩ, R3 = 8.21 kΩ, R4 = 217.25 kΩ, C5 = 150 pF, (Z_C = 26.5 kΩ at 40 kHz), C6 = 47 pF (Z_C = 84.6 kΩ at 40 kHz)

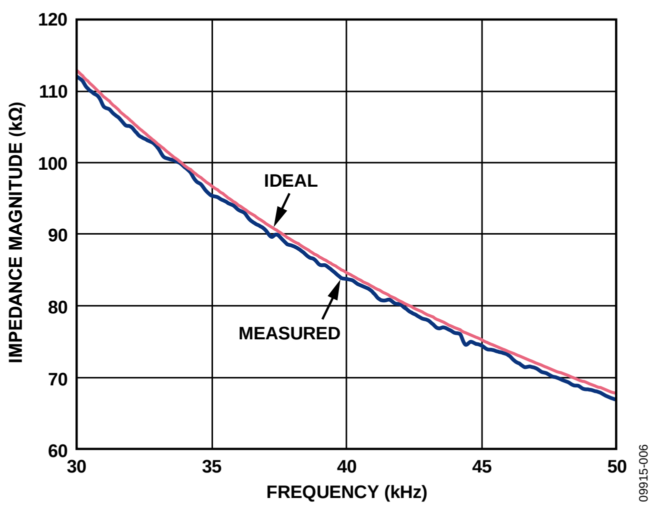

Figure 6. Magnitude Result for Z_C = 47 pF, R_{CAL} = 99.85 kΩ

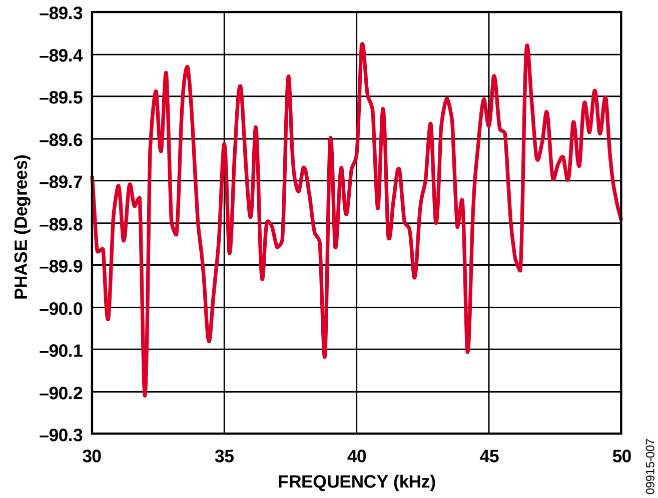

Figure 7. Phase Result for Z_C = 47 pF, R_{CAL} = 99.85 kΩ

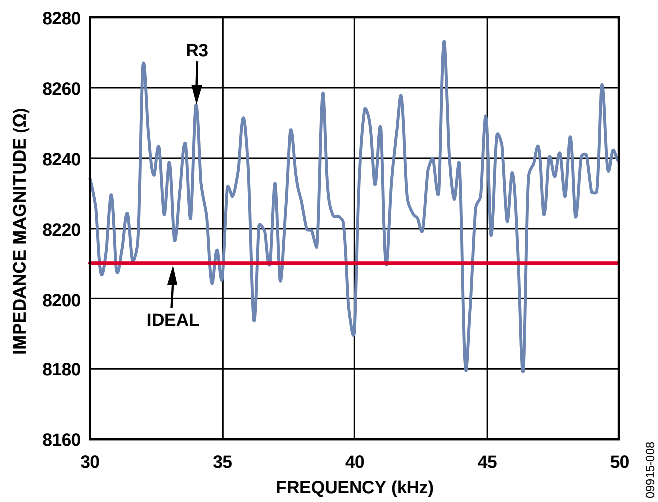

Figure 8. Z_C = 8.21 kΩ, R_{CAL} = 99.85 kΩ

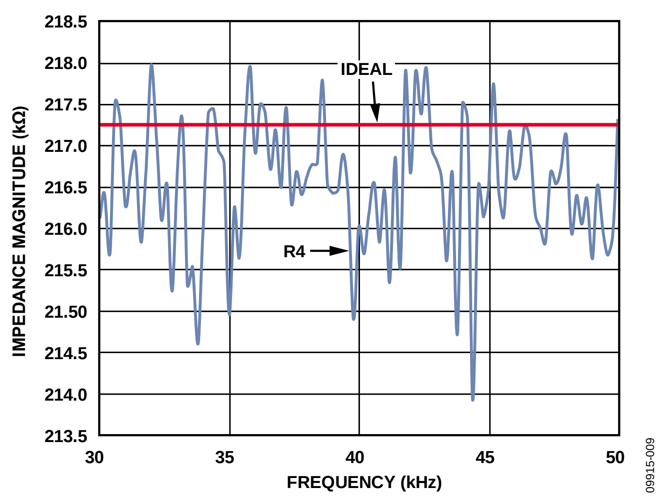

Figure 9. Z_C = 217.25 kΩ, R_{CAL} = 99.85 kΩ

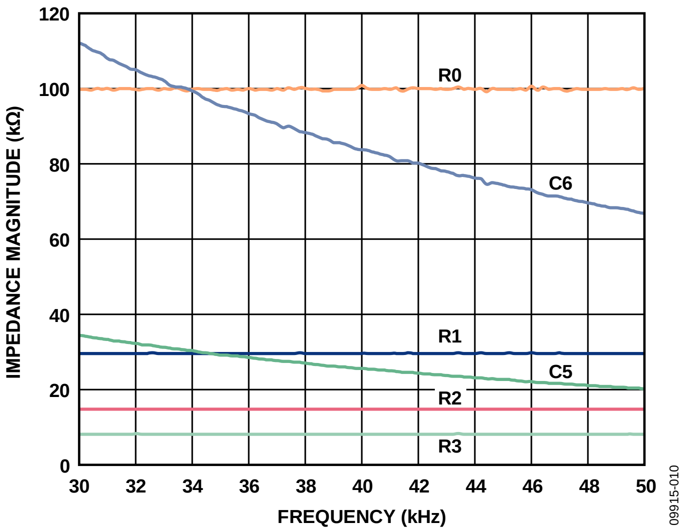

Figure 10. Magnitude Results for Example 2: R1, R2, R3, C5, C6

Example 3: Parallel R-C (R||C) Measurement

An R||C type measurement was also made using the configuration, using an R_{CAL} of 1 kΩ, an R of 10 kΩ, and a C of 10 nF, measured across a frequency range of 4 kHz to 100 kHz. The magnitude and phase results vs. ideal are plotted in Figure 11 and Figure 12.

Table 5. R||C Impedance Range Setup for V_{DD} = 3.3 V Supply Voltage

Parameter	Value
Voltage Peak-to-Peak (V p-p)	0.383 V (Range 3)
Number of Settling Time Cycles	15
MCLK	16 MHz
R_{CAL}	1 kΩ
R_{FB}	1 kΩ
Excitation Frequency Range	4 kHz to 100 kHz
Unknown Impedance R||C	R = 10 kΩ, C = 10 nF

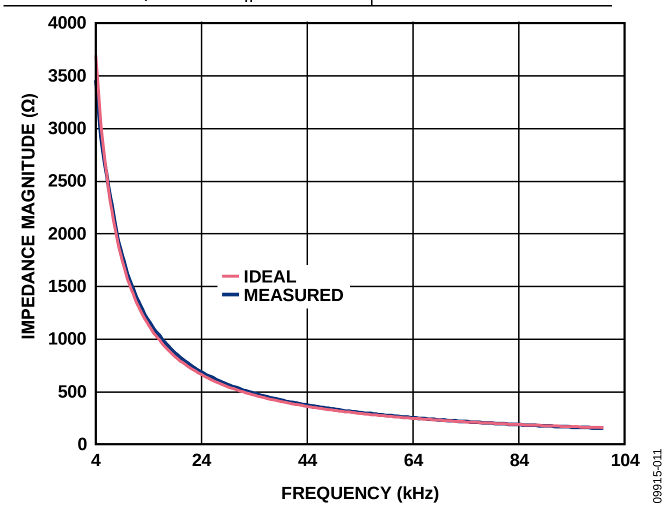

Figure 11. Magnitude Results for Z_C = 10 kΩ||10 nF, R_{CAL} = 1 kΩ

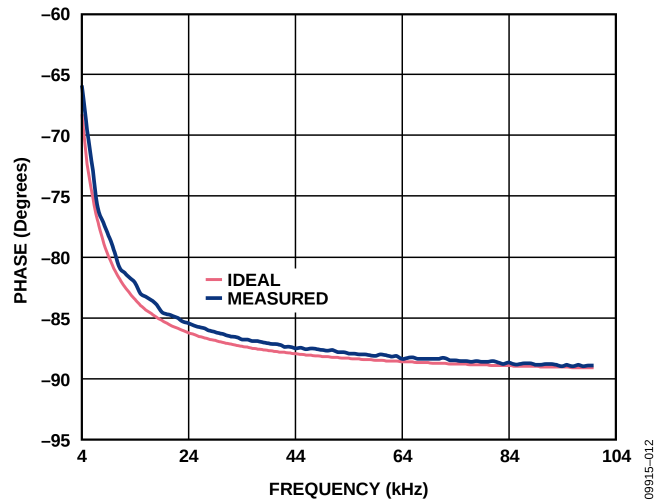

Figure 12. Phase Results for Z_C = 10 kΩ||10 nF, R_{CAL} = 1 kΩ

Setup and Test

The evaluation board software is the software used on the EVAL-AD5933EBZ. Refer to the technical note available on the CD provided with the evaluation board for details on the board setup. Note that there are alterations to the schematic. Link connections on the EVAL-AD5933EBZ board are listed in Table 4. In addition, note that the location for R_{FB} is located at R3 on the evaluation board, and the location for $Z_{UNKNOWN}$ is C4.

Table 6. Link Connections for EVAL-AD5933EBZ

Link Number	Default Position
LK1	Open
LK2	Open
LK3	Insert
LK4	Open
LK5	Insert
LK6	A

Complete setup and operation for the hardware and software for the evaluation board can be found in User Guide UG-364.

COMMON VARIATIONS

Other op amps can be used in the circuit, such as the ADA4528-1, AD8628, AD8629, AD8605, and AD8608.

Switching Options for System Applications

For this particular circuit, the $Z_{UNKNOWN}$ and R_{CAL} were interchanged manually. However, in production, use a low on-resistance switch. The choice of the switch depends on how large the unknown impedance range is and how accurate the measurement result needs to be. The examples in this circuit note use just one calibration resistor, and so a low on-resistance switch, such as the ADG849, can be used as shown in Figure 13. Multichannel switch solutions, such as the quad ADG812, can also be used. The errors caused by the switch resistance on the $Z_{UNKNOWN}$ are removed during calibration, but by choosing a very low R_{ON} switch, the effects can be further minimized.

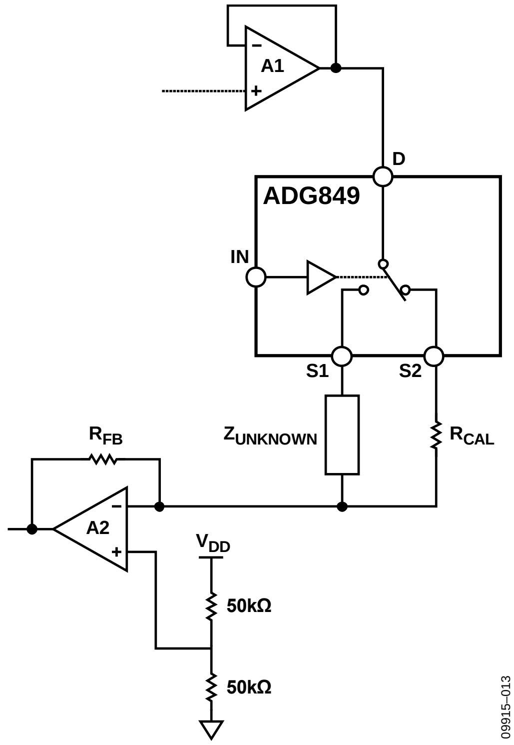

Figure 13. Switching Between R_{CAL} and Unknown Z Using the ADG849 Ultralow R_{ON} SPDT Switch (Simplified Schematic, All Connections and Decoupling Not Shown)

LEARN MORE

CN-0217 Design Support Package: http://www.analog.com/CN0217-DesignSupport

MT-085 Tutorial, "Fundamentals of Direct Digital Synthesis (DDS)," Analog Devices.

Buchanan, David, "Choosing DACs for Direct Digital Synthesis," AN-237 Application Note, Analog Devices.

Riordan, Liam, "AD5933 Evaluation Board Example Measurement," AN-1053 Application Note, Analog Devices.

UG-364 User Guide for AD5933 Evaluation Board

ADIsimDDS Design and Evaluation Tool

AD5933/AD5934 Demonstration and Design Tool

Data Sheets and Evaluation Boards

AD5933 Data Sheet

AD5933 Evaluation Board

AD5934 Data Sheet

AD5934 Evaluation Board

AD8606 Data Sheet

ADG849 Data Sheet

ADG812 Data Sheet

REVISION HISTORY

3/13—Rev. 0 to Rev. A

Updated Table Numbers; Renumbered Sequentially....................3
Changes to Evaluation and Design Support Section 1
Changes to Setup and Test Section and Table 6 5
Changes to Learn More Section 6

6/11—Revision 0: Initial Version