

# Circuit for protecting ADS131M0x ADC from electrical overstress



Data Converters

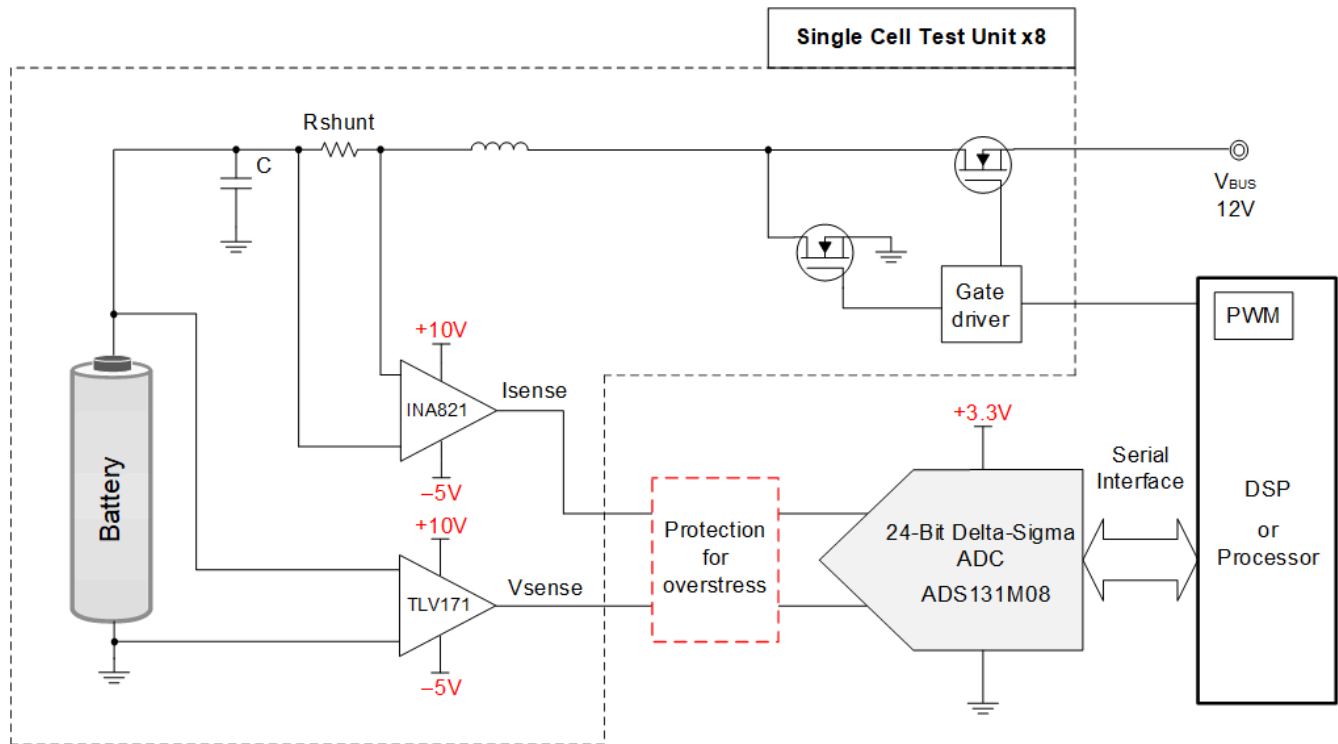
Dale Li

Specifications on ADS131M0x		Minimum (AGND = 0V)	Maximum (AVDD = 3.3V)
Absolute Maximum Ratings	Analog Input Voltage ( $V_{IN\_Abs}$ )	-1.6V	+3.6V
	Analog Input Current ( $I_{IN\_Abs}$ )	-10mA	+10mA
Analog Input Range ( $V_{IN}$ at Gain=1 and $V_{REF}=1.2$ V)	Differential Input	-1.2V	+1.2V
	Single-ended Input	-1.2V	+1.2V

## Design Description

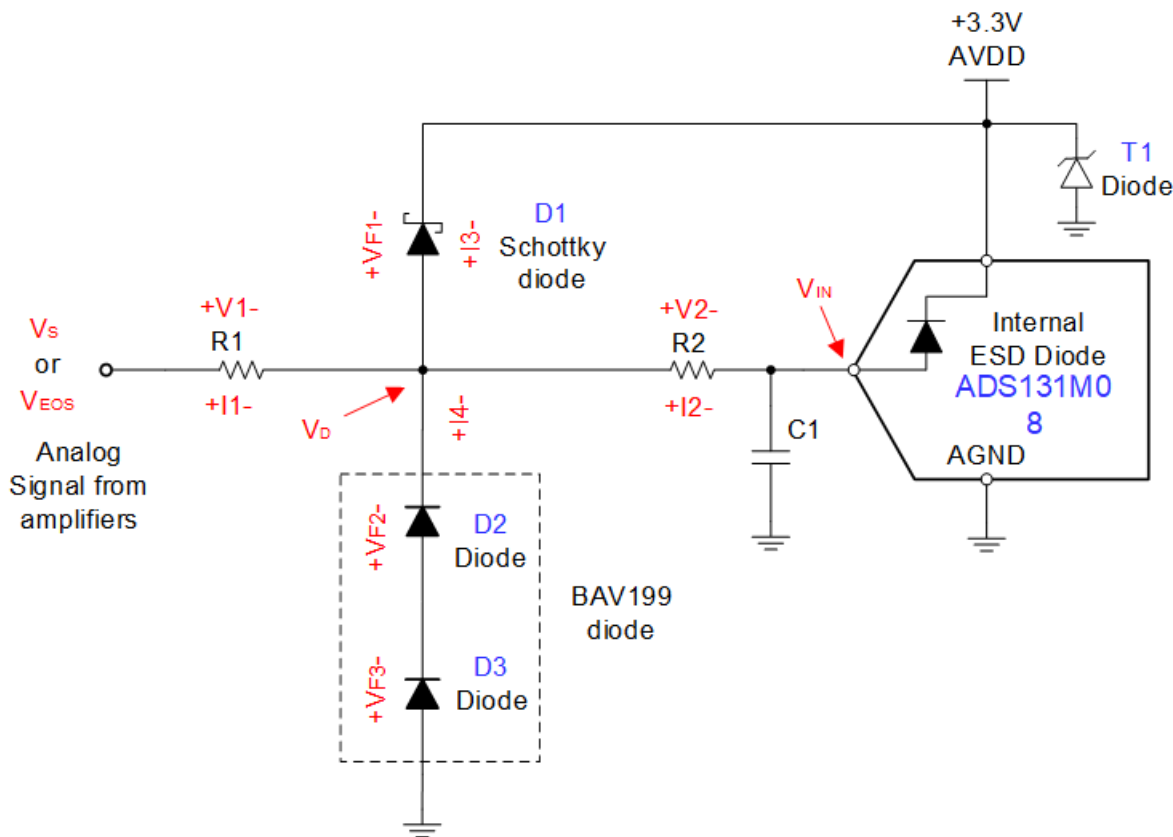
This circuit shows an external solution to protect [ADS131M02](#), [ADS131M03](#), [ADS131M04](#), [ADS131M06](#), and [ADS131M08](#) Delta-Sigma ADCs from electrical overstress (EOS). The protection is implemented with external Schottky diodes and switching diodes. This document shows how the Schottky diodes and switching diodes can be used with current-limiting resistors to implement the external protection clamp for the overstress signal and maintain a minimum impact on performance, especially signal-to-noise ratio (SNR) and total harmonic distortion (THD). This circuit is useful in the following end equipment: [Battery test](#), [Semiconductor test](#), [Electricity meter](#), [Power quality analyzer](#), and [Power quality meter](#). For protecting high-voltage SAR ADCs from electrical overstress, see [Input protection for high-voltage ADC circuit with TVS diode](#) and [Circuit for protecting ADC with TVS diode and PTC fuse](#). For protecting low-voltage SAR ADC from electrical overstress, see [Circuit for protecting low-voltage SAR ADCs from electrical overstress with minimal impact on performance](#).

The following figure comes from the [Digital Control Reference Design for Cost-Optimized Battery Test Systems Reference Design](#) in the [Battery Test](#) application. During an electrical overstress event, this circuit can potentially apply damaging voltages and currents to the inputs of the ADS131M08 ADC: the voltage from the amplifiers (INA821 and TLV171) can reach the power supply voltages (+10V or -5V), and the overstress current from the amplifiers can be as high as the short-circuit current for each respective amplifier.



## Design Notes

1. The BAT54 Schottky diode (D1) is selected to protect the ADS131M08 from positive electrical overstress signals because it has lower forward voltage, lower leakage current, and lower capacitance than conventional transient voltage suppressor (TVS) diodes, which can minimize the additional errors caused by these factors.
2. The BAV199 dual series switching diode with a typical 0.9-V forward voltage at 1-mA forward current is selected for D2 and D3 to protect the ADC from negative overstress signals in this design. The BAT54 Schottky diode features a typical 0.3-V forward voltage at 1-mA forward current, so four single Schottky diodes (BAT54) can be used against negative overstress signals as an alternative solution.
3. The series resistors (R1 and R2) are used to limit fault current for protecting the diodes and the ADC. They also help to clamp the input overstress signal on the diodes by selecting a proper resistance.
4. Select a C0G type capacitor for C1 in the front-end RC filter to minimize the distortion because the capacitance of the C0G capacitor is more stable and the voltage, frequency, and temperature coefficient of the C0G capacitor are smaller than other type capacitors including X7R, X5R and Z5U.
5. A TVS or Zener diode (T1) is recommended for the power supply clamp as the power supply may not be able to sink the fault current that feeds through the protection diode (D1) and internal ESD diode on the ADC.
6. See the [Electrical Overstress on Data Converters](#) video in the [TI Precision Labs - ADCs](#) video series for a theoretical explanation of overstress on data converters. This series discusses details on protection solutions for different types of ADCs, including diode selection and current-limiting resistor selection.



$V_s$ : normal operation signal.

$V_{Eos}$ : electrical overstress signal.

## Component Selection

- The following table lists the output voltage and current range for the INA821 and TLV171 amplifiers. These are maximum overstress voltages and currents that may be applied to the ADS131M08 inputs. These input parameters should be limited to within the absolute maximum ratings in step 2 to protect the ADS131M08 from damage.

INA821 Output Range		TLV171 Output Range	
Output Voltage ( $V_O$ )	$-5V \leq V_O \leq +10V$	Output Voltage ( $V_O$ )	$-5V \leq V_O \leq +10V$
Short-circuit current ( $I_{SC}$ )	$-20mA \leq I_{SC} \leq +20mA$	Short-circuit current ( $I_{SC}$ )	$-35mA \leq I_{SC} \leq +25mA$

Since the specifications of the TLV171 are the worst case, all specifications from the TLV171 amplifier are used to design a protection circuit that works for both voltage ( $V_{sense}$ ) and current ( $I_{sense}$ ) measurement channels on the ADS131M08.

The electrical overstress voltage from the ADS131M08 can reach up to the power supply of the TLV171, so the  $V_{EOS\_MAX} = +10V$  and the  $V_{EOS\_MIN} = -5V$ . The electrical overstress current from the ADS131M08 can be as high as the short-circuit current of the TLV171, so the  $I_{1\_MAX} = I_{SC\_MAX} = +25mA$  and the  $I_{1\_MIN} = I_{SC\_MIN} = -35mA$ .

- The input voltage range of the ADS131M08 is set as the absolute maximum voltage ( $V_{IN\_Abs}$ ) before turning on the internal ESD diode. The input current range of the ADS131M08 is set as the absolute maximum current ( $I_{IN\_Abs}$ ) that the internal ESD diode can support continuously.

The following table, which comes from the absolute maximum ratings table in the [ADS131M08 8-Channel, Simultaneously-Sampling, 24-Bit, Delta-Sigma ADC Data Sheet](#), shows that the absolute maximum input voltage on the ADS131M08 is 3.6V when AVDD is 3.3V, so any positive electrical overstress signal higher than 3.3V should be clamped to protect the ADS131M08 inputs. In this solution, the BAT54 Schottky diode is selected as D1 to protect the ADC from a positive electrical overstress signal because it has a small forward drop as well as reasonable low leakage and capacitance.

ADS131M08		Minimum (AGND = 0V)	Maximum (AVDD = 3.3V)
Absolute Maximum Ratings	Analog Input Voltage ( $V_{IN\_Abs}$ )	-1.6V	+3.6V
	Analog Input Current ( $I_{IN\_Abs}$ )	-10mA	+10mA

- The current-limiting resistor, R1, is selected as the larger resistor values between the  $R_{1\_P}$ , calculated from the following [equation](#) for positive voltage overstress, and the  $R_{1\_N}$ , calculated from the [equation](#) for negative voltage overstress.

- Positive overstress voltage:

For a positive overstress voltage that is greater than +3.3V, the Schottky diode D1 operates in a forward state. The maximum input current in the circuit is +25mA from the TLV171. The forward voltage of D1 is around 0.4V at 25-mA forward current at 25°C based on the BAT54 data sheet from Diodes Incorporated. Therefore,  $V_{F1} = 0.4V$  and  $I_{1\_POS} = I_{SC\_MAX} = 25mA$ .

The required resistance of R1 under the positive overstress of +10V ( $R_{1\_P}$ ) can be calculated as:

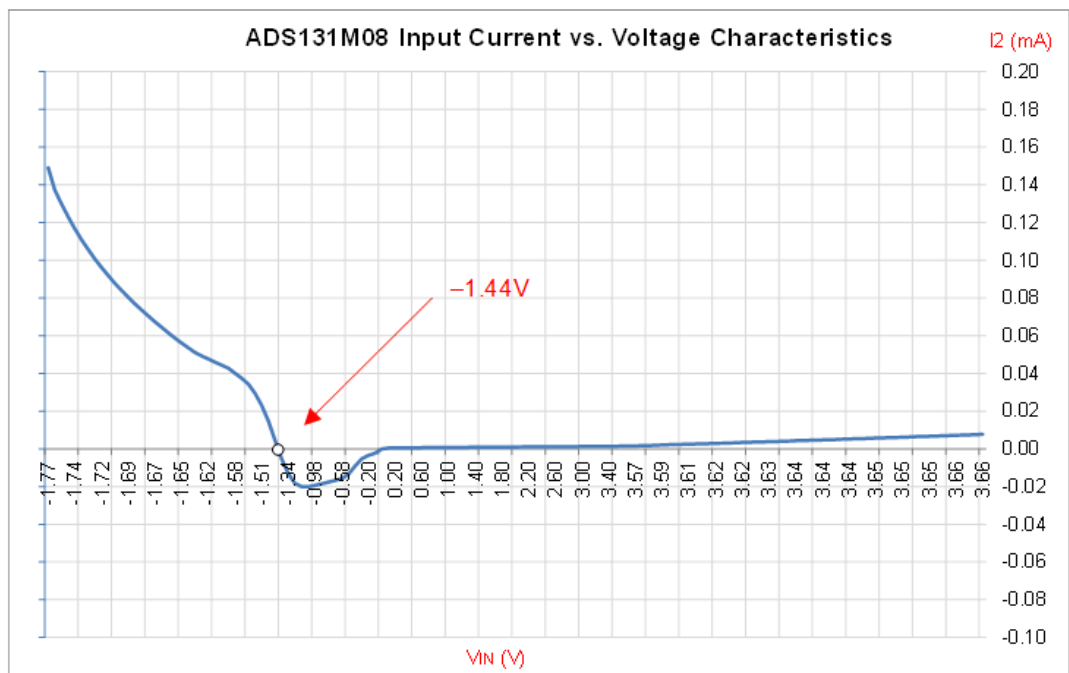
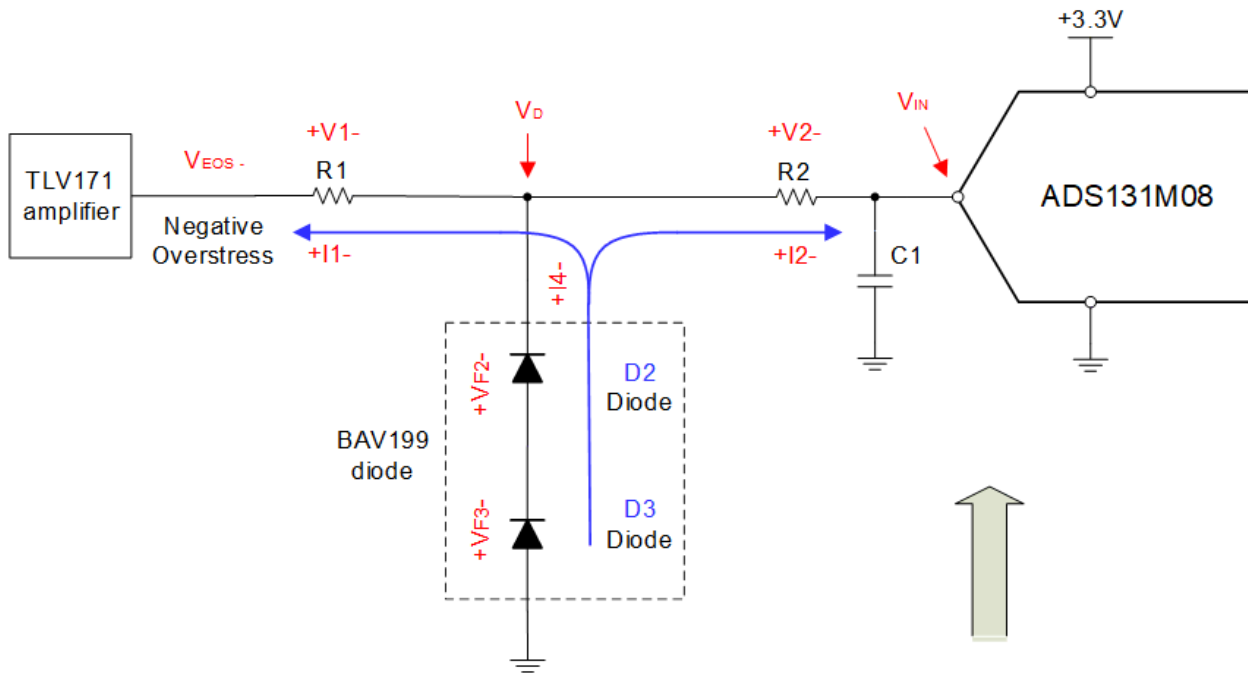
$$R_{1\_P} = \frac{V_{EOS\_MAX} - V_{F1} - AVDD}{I_{1\_POS}} = \frac{10V - 0.4V - 3.3V}{25mA} = 252\Omega$$

- Negative overstress voltage:

The ADS131M08 has an integrated negative charge pump that allows operating for input voltages below ground (AGND) with a unipolar supply. When a negative overstress voltage lower than -1.44V is applied to the ADS131M08 input, the internal switch is turned on and the current ( $I_2$ ) flows into the ADC input as shown in the [input current and voltage characteristics curve](#) on the ADS131M08. The blue lines in the

circuit show the current flow direction for a negative overstress voltage lower than  $-1.44\text{V}$  applied on the ADS131M08 input.

The minimum input voltage rating of the ADS131M08 ( $V_{IN\_MIN}$ ) is  $-1.6\text{V}$  which is the minimum safe voltage to avoid damage to the device. Therefore, to achieve a minimum voltage signal of  $-1.6\text{V}$  on the ADC input pin ( $V_{IN}$ ), the node voltage,  $V_D$ , should be equal to or greater than  $-1.6\text{V}$ . Two BAV199 diodes are used to clamp the negative overstress signal on  $V_D$  with both diodes conducting in the forward direction. Hence, the forward voltage on each BAV199 diode is expected to be equal to or less than  $0.8\text{V}$ . The D1 Schottky diode in the protection circuit operates in reverse state when a negative overstress signal appears. The leakage current on the D1 Schottky diode (BAT54) is only  $2\mu\text{A}$  so the D1 diode is neglected in the following circuit.



The forward current is found from the typical forward characteristics curve in the [BAV199 data sheet](#) from Diodes Incorporated. To limit the forward voltage of each diode on the BAV199 to 0.8V ( $V_{F2} = V_{F3} = 0.8V$ ), the forward current ( $I_4$ ) needs to be limited to 4mA.

Since the  $V_D$  is equal to  $V_{IN\_MIN}$  (-1.6V), the 4-mA current flows into the TLV171 amplifier and the current  $I_1$  under a negative overstress voltage of -5V ( $I_{1\_NEG}$ ) is equal to -4mA. Therefore, the required resistance of R1 under a negative overstress of -5V ( $R_{1\_N}$ ) can be calculated as:

$$R_{1\_N} = \frac{V_{EOS\_MIN} - (-V_{F2} - V_{F3})}{I_{1\_NEG}} = \frac{-5V - (-0.8V - 0.8V)}{-4mA} = 850\Omega$$

The larger of the two resistance values from the previous [equations](#) is 850Ω. A large resistance is helpful to limit the electrical overstress current and clamp the electrical overstress voltage. Hence, R1 is selected as 1kΩ to account for extra design margin.

- Resistor Power Rating:

In the following [equation](#), the fault current and power dissipated is calculated for R1 during a positive electrical overstress event which is the worse-case stress for R1.

$$P_{R1} = \frac{(V_{EOS\_MAX} - V_{F1} - AVDD)^2}{R_1} = \frac{(10V - 0.4V - 3.3V)^2}{1k\Omega} = 39.69mW$$

The objective is to make sure that the correct power rating is selected for R1. The minimum power rating for R1 is calculated to be 39.69mW according to the previous [equation](#). A resistor with a 0.1-W power rating can be selected to account for extra design margin.

- The resistor, R2, acts as a low-pass filter with the capacitor C1 and also limits the current to the ADC input under a fault condition. The value for R2 is selected as the larger resistance between the  $R_{2\_P}$ , calculated from the [equation](#) for positive voltage overstress and  $R_{2\_N}$ , calculated from the following [equation](#) for negative voltage overstress.

- Positive overstress voltage:

The absolute maximum input current rating ( $I_{IN\_Abs}$ ) of the ADS131M08 is ±10mA. The smaller the input current flowing to the ADC inputs, the more reliably the circuit will perform. The ±1mA is used as the target maximum input current to the ADC to calculate for margin with one order of magnitude less than the absolute maximum ratings. Therefore,  $I_{2\_POS} = \pm 1mA$ . The forward voltage of D1 is around 0.4V at 25 mA forward current at 25°C based on the BAT54 data sheet from Diodes Incorporated. Therefore,  $V_{F1} = 0.4V$ .  $V_{IN\_MAX} = 3.6V$  which is the maximum absolute input voltage rating of the ADS131M08.

The required resistance of R2 under a positive over stresses voltage of +10V ( $R_{2\_P}$ ) can be calculated as:

$$R_{2\_P} = \frac{(V_{F1} + AVDD) - V_{IN\_MAX}}{I_{2\_POS}} = \frac{(0.4V + 3.3V) - 3.6V}{1mA} = 100\Omega$$

- Negative overstress voltage:

Since the node voltage,  $V_D$ , is designed to be equal to the  $V_{IN\_MIN}$  which is the minimum input voltage rating of the ADS131M08 (-1.6V) under a negative overstress voltage, very little current will flow into the ADC input. Therefore, the required resistance of R2 under a negative over stresses voltage of -5V ( $R_{2\_N}$ ) is not critical.

The  $R_{2\_P}$  value is used to select R2 as the current into the ADC should be minimal during negative overstress conditions because the diodes (D2 and D3) limit the input voltage to avoid the overstress region. Therefore, R2 is selected as 100Ω.

- Resistor Power Rating:

In the following [equation](#), the fault current and power dissipated is calculated in R2 during a positive electrical overstress event, which is the worse-case stress for R2. The objective is to make sure that the correct power rating is selected for R2.  $V_{F1} = 0.4V$  which is the forward voltage of BAT54 (D1) at 25-mA forward current at 25°C.  $V_{IN\_MAX} = 3.6V$  which is the maximum absolute input voltage rating of the ADS131M08.

$$P_{R2} = \frac{(V_{F1} + AVDD - V_{IN\_MAX})^2}{R_2} = \frac{(0.4V + 3.3V - 3.6V)^2}{100\Omega} = 0.1mW$$

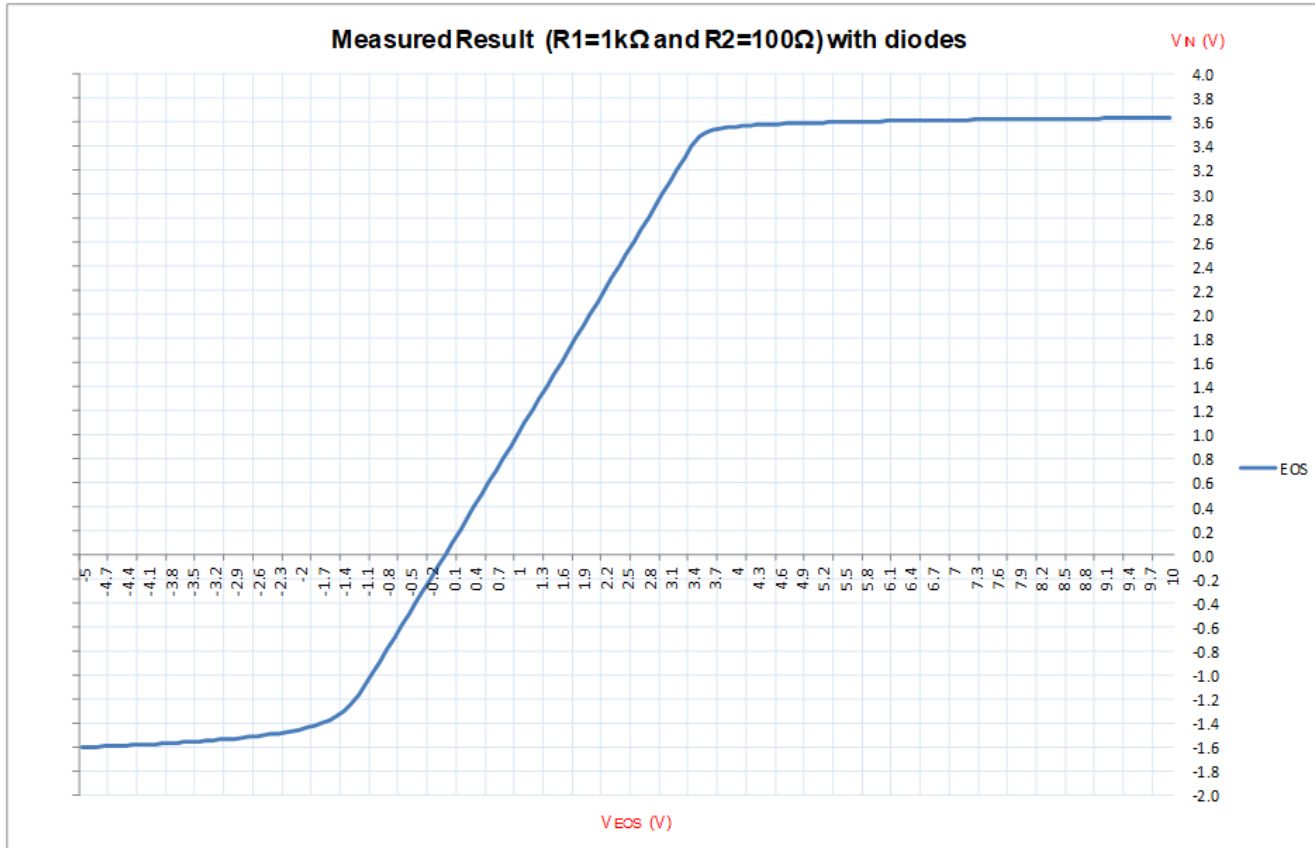
The minimum power rating for R1 is calculated to be 0.1mW according to the previous [equation](#). A resistor with a 0.1-W power rating can be selected to account for extra design margin. The resistance of R2 can be adjusted to set the cutoff frequency of the filter as step 5 shows.

- The capacitor C1 in parallel with R2 is used to filter the noise from the front-end circuit. The [equation](#) for the cutoff frequency based on the input resistors and capacitors follows. The exact value may not be very critical so we use a standard value of 10nF in the following formula.

$$f_c = \frac{1}{2 \times \pi \times (R_1 + R_2) \times C_1} = \frac{1}{2 \times \pi \times (1k\Omega + 100\Omega) \times 10nF} = 14.4kHz$$

## ADC Input Overvoltage Condition

The following figure shows the voltage ( $V_{IN}$ ) measured on the ADC input with a multimeter when a continuous overstress signal (VEOS) is applied from  $-5V$  to  $+10V$ . Note that the external BAT54 Schottky diode (D1) is turned on for positive overvoltage signals and the external BAV199 dual series switching diodes (D2 and D3) are turned on for negative overvoltage signals. The overstress signals have been clamped to approximate  $+3.6V$  and  $-1.6V$ , which is equal to the absolute maximum input voltage ratings ( $V_{IN\_Abs}$ ) on the ADS131M08, so the ADC is successfully protected from external overvoltage event.





## AC (SNR and THD) Performance Checked on Hardware

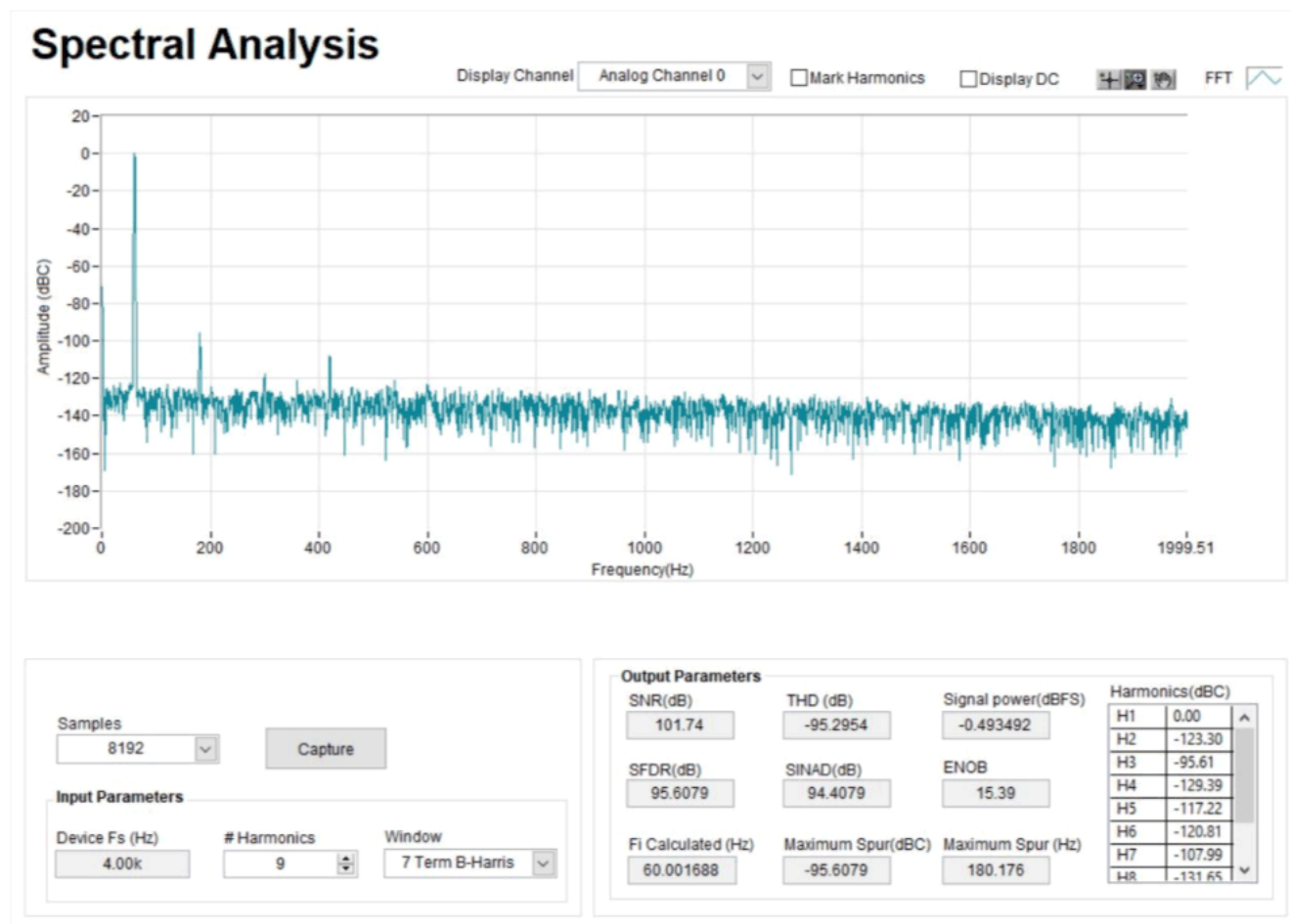
The following table shows the performance which is measured using [ADS131M08EVM](#) hardware with a schottky diode (BAT54) and dual-series Switching diode (BAV199) and the [Delta-Sigma ADC Evaluation software](#).

ADS131M08	Specification in Data Sheet	Test 1	Test 2
SNR	101 dB	101.7 dB	101.9 dB
THD	-100 dB	-95.3 dB	-95.2 dB

Test condition:

1. Test 1: R1 = 1kΩ, R2 = 100Ω with BAT54 (D1) and BAV199 (D2 and D3).
2. Test 2: R1 = 1kΩ, R2 = 100Ω without BAT54 (D1) and BAV199 (D2 and D3).
3. Protection: a same protection circuit is designed on AINxP and AINxN input of ADS131M08 and a differential capacitor is applied between the AINxP and AINxN input.
4. Test signal: a differential sinusoidal wave with 60-Hz frequency and -0.5dBFS amplitude, 4-kSPS data rate, Gain = 1, OSR = 1024 and internal voltage reference.

The measured SNR performance with all the protection circuits including the BAT54 and BAV199 diode meets the typical specification in the [ADS131M08 8-Channel, Simultaneously-Sampling, 24-Bit, Delta-Sigma ADC Data Sheet](#). The measured THD performance is worse than the typical THD specification in the ADS131M08 data sheet. An additional test (Test 2) shows that the slightly worse THD performance in Test 1 is not caused by the protection diodes and it is caused by the combination between the large resistance of these two series (R1 and R2) and the parameter of ADC input structure that varies with the voltage applied on the ADC input. The following figure shows the measured spectral analysis in Test 1.



## Accuracy Checked on Hardware

The following table shows the measured gain error with all the protection circuit including BAT54, BAV199 diode, 1-k $\Omega$  and 100- $\Omega$  series resistors. The input is a differential signal for the measurement. At room temperature without calibration, a gain error is present. Once a calibration (two point calibration) is applied to the measured results from the ADS131M08, the gain error is minimized to nearly zero.

Measurements at Room Temperature (25°C)					
V <sub>S</sub> (V)	Measured V <sub>S</sub> (V)	Code	Uncalibrated V <sub>S</sub> (V)	Voltage Error Without Calibration (%)	Voltage Error With Calibration (%)
1.14	1.139898	7913462	1.132030	0.690	0.000
1.0	0.999916	6941921	0.993050	0.687	0.002
0.8	0.799941	5553901	0.794492	0.681	0.003
0.5	0.499973	3471737	0.496636	0.667	0.004
0.05	0.050034	348389	0.049837	0.393	0.000
0	0.000043	1068	0.000153	—	—
-0.05	-0.049958	-345711	-0.049454	1.008	0.000
-0.5	-0.499903	-3469100	-0.496259	0.729	0.003
-0.8	-0.799879	-5551380	-0.794131	0.719	0.004
-1.0	-0.999867	-6939513	-0.992705	0.716	0.003
-1.14	-1.139845	-7910985	-1.131675	0.717	0.000

## Design References

See the [Analog Engineer's Circuit Cookbooks](#) for TI's comprehensive circuit library.

## Design Featured Devices

Device	Key Features	Link	Other Possible Devices
ADS131M08	24-bit, 32-kSPS, 8-channel, simultaneous sampling delta-sigma ADC	<a href="https://www.ti.com/product/ADS131M08">https://www.ti.com/product/ADS131M08</a>	<a href="https://www.ti.com/adcs">https://www.ti.com/adcs</a>
ADS131M06	24-bit, 32-kSPS, 6-channel, simultaneous sampling delta-sigma ADC	<a href="https://www.ti.com/product/ADS131M06">https://www.ti.com/product/ADS131M06</a>	<a href="https://www.ti.com/adcs">https://www.ti.com/adcs</a>
ADS131M04	24-bit, 32-kSPS, 4-channel, simultaneous sampling delta-sigma ADC	<a href="https://www.ti.com/product/ADS131M04">https://www.ti.com/product/ADS131M04</a>	<a href="https://www.ti.com/adcs">https://www.ti.com/adcs</a>
ADS131M03	24-bit, 32-kSPS, 3-channel, simultaneous sampling delta-sigma ADC	<a href="https://www.ti.com/product/ADS131M03">https://www.ti.com/product/ADS131M03</a>	<a href="https://www.ti.com/adcs">https://www.ti.com/adcs</a>
ADS131M02	24-bit, 32-kSPS, 2-channel, simultaneous sampling delta-sigma ADC	<a href="https://www.ti.com/product/ADS131M02">https://www.ti.com/product/ADS131M02</a>	<a href="https://www.ti.com/adcs">https://www.ti.com/adcs</a>
ADS131B04-Q1	Automotive, 24-bit, 32-kSPS, 4-channel, simultaneous sampling delta-sigma ADC	<a href="https://www.ti.com/product/ADS131B04-Q1">https://www.ti.com/product/ADS131B04-Q1</a>	<a href="https://www.ti.com/adcs">https://www.ti.com/adcs</a>
INA821	High bandwidth (4.7MHz), low noise (7nV/ $\sqrt{\text{Hz}}$ ), precision (35 $\mu\text{V}$ ), low-power, instrumentation amp	<a href="https://www.ti.com/product/INA821">https://www.ti.com/product/INA821</a>	<a href="https://www.ti.com/inas">https://www.ti.com/inas</a>
TLV171	36V Low-Power RRO General Purpose Operational Amplifier	<a href="https://www.ti.com/product/TLV171">https://www.ti.com/product/TLV171</a>	<a href="https://www.ti.com/opamps">https://www.ti.com/opamps</a>

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