

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

### Features

- AEC-Q100 Qualified for Automotive Applications:
  - Grade 1:  $-40^{\circ}\text{C}$  to  $125^{\circ}\text{C}$   $T_A$
- 16-bit, 8-kSPS, 4-channel ADC
- Wide Supply Range: 2.7 V to 5.5 V
- Programmable Data Rate:
  - 64 SPS to 8 kSPS
- Single-Cycle Settling
- Supporting Four Single-Ended or Two Differential Inputs
- Internal PGA
- Internal Low-drift Voltage Reference
- Internal Temperature Sensor
- SPI Compatible Interface
- Package: MSOP3x3-10
- Wide Operating Temperature Range:  $-40^{\circ}\text{C}$  to  $+125^{\circ}\text{C}$

### Applications

- Current-shunt Measurements
- Voltage Measurements
- Temperature Measurements

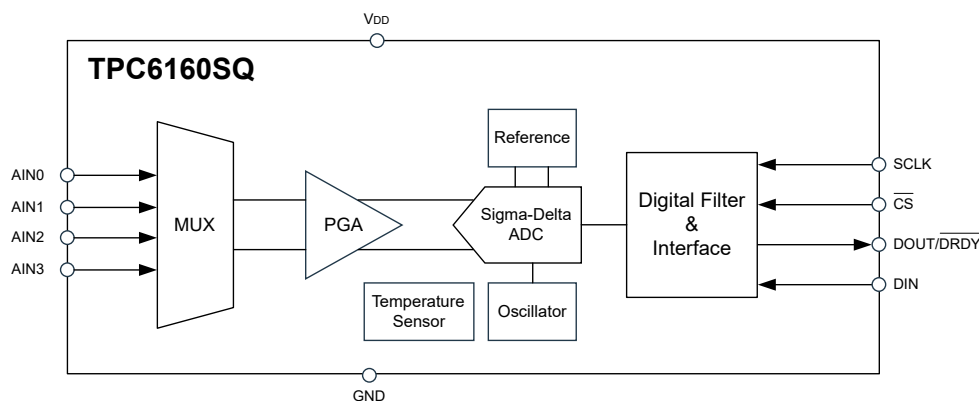
### Description

The TPC6160SQ is a 16-bit Sigma-Delta ADC for high precision and low power measurement. The TPC6160SQ features an internal programmable gain amplifier (PGA), voltage reference, oscillator, digital filter, and temperature sensor. The device supports a wide range of supply voltages from 2.7 V to 5.5 V.

The data rate of the TPC6160SQ is configurable from 64 SPS to 8 kSPS. The PGA provides input ranges spanning from  $\pm 256$  mV to  $\pm 6.144$  V, with the analog input negative voltage down to  $-128$  mV, which allows both high precision positive and negative signal measurement. The integrated input mux supports two differential pairs or four independent single-ended inputs. The internal temperature sensor can be used for general temperature monitoring or thermal-couple cold-junction compensation.

The TPC6160SQ can be set in single-shot conversion mode or continuous conversion mode. Single-shot mode features power down after conversion, which is suitable for low-power applications. The digital interface supports communication with various host controllers with SPI-compatible serial interface. The TPC6160SQ is available in MSOP10 package and operates from  $-40^{\circ}\text{C}$  to  $+125^{\circ}\text{C}$ .

### Functional Block Diagram



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**Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with  
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**Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with  
Internal Reference and Temperature Sensor****Product Family Table**

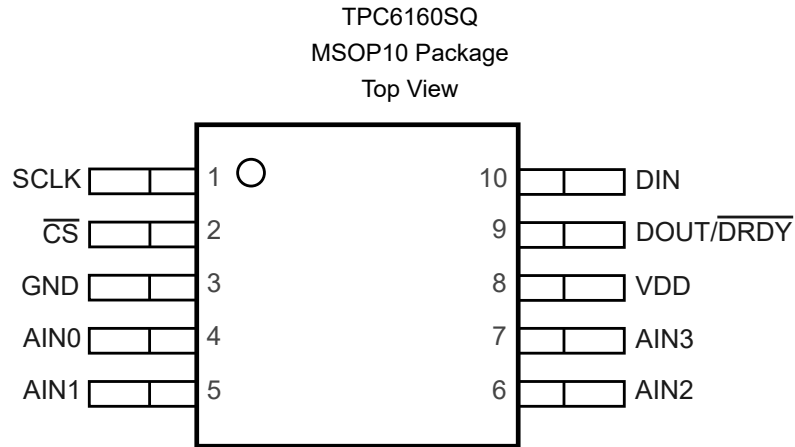
Order Number	Channels	Resolution	Throughput	Package	Interface	Grade
TPC6160SQ-VS2R-S	4	16 Bits	8 kSPS	MSOP10	SPI	Automotive

**Revision History**

Date	Revision	Notes
2024-11-13	Rev.A.0	Initial release.

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

### Pin Configuration and Functions



**Table 1. Pin Functions: TPC6160SQ**

Pin		Type <sup>(1)</sup>	Description
No.	Name		
1	SCLK	DI	Serial clock input. This pin acts as the serial clock input for data transfers.
2	$\overline{CS}$	DI	Chip Select. This active low logic input frames the data transfer. If not used, connect this pin to GND.
3	GND	P	Ground.
4	AIN0	AI	Analog Input for Channel 0. If not used, float this pin or tie to VDD.
5	AIN1	AI	Analog Input for Channel 1. If not used, float this pin or tie to VDD.
6	AIN2	AI	Analog Input for Channel 2. If not used, float this pin or tie to VDD.
7	AIN3	AI	Analog Input for Channel 3. If not used, float this pin or tie to VDD.
8	VDD	P	Power supply. Connect a 0.1 $\mu$ F power supply decoupling capacitor to GND.
9	DOUT/ $\overline{DRDY}$	DO	Serial data output combined with data ready; active low.
10	DIN	DI	Serial data input.

(1) AI is analog input, GND is ground, P is power supply, DI is digital input, and DO is digital output.

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

### Specifications

#### Absolute Maximum Ratings <sup>(1)</sup>

Parameter		Min	Max	Unit
Analog Voltage	Analog Input Voltage to GND	GND – 0.3	VDD + 0.3	V
Digital Voltage	Digital Input Voltage to AGND	GND – 0.3	VDD + 0.3	V
	Digital Output Voltage to AGND	GND – 0.3	VDD + 0.3	V
Supply Voltage	VDD to GND	–0.3	5.5	V
Input Current (continuous)	Any Pin except Power Supply Pins	–10	10	mA
T <sub>J</sub>	Maximum Junction Temperature		150	°C
T <sub>A</sub>	Operating Temperature Range	–40	125	°C
T <sub>STG</sub>	Storage Temperature Range	–65	150	°C

(1) Stresses beyond those listed under Absolute Maximum Ratings may cause permanent damage to the device. Exposure to any Absolute Maximum Rating condition for extended periods may affect device reliability and lifetime.

#### ESD, Electrostatic Discharge Protection

Symbol	Parameter	Condition	Minimum Level	Unit
HBM	Human Body Model ESD	AEC Q100-002 <sup>(1)</sup>	±4	kV
CDM	Charged Device Model ESD	AEC Q100-011	±1.5	kV

(1) AEC Q100-002 indicates that HBM stressing shall be in accordance with the ANSI/ESDA/JEDEC JS-001 specification.

#### Recommended Operating Conditions

Parameter			Min	Typ	Max	Unit
VDD	Power Supply	VDD to GND	2.7		5.5	V
FSR	Full-scale Input Voltage <sup>(1)</sup>	V <sub>IN</sub> = V <sub>(AINP)</sub> – V <sub>(AINN)</sub>	±0.256		±6.144	V
V <sub>(AINx)</sub>	Absolute Input Voltage		–0.128		VDD	V
Digital input Voltage	Absolute Input Voltage		GND		VDD	V
T <sub>A</sub>	Operating Ambient Temperature		–40		125	°C

(1) This parameter expresses the full-scale range of the ADC scaling. No more than VDD + 0.3 V or 5.5 V (whichever is smaller) must be applied to this device.

#### Thermal Information

Package Type	θ <sub>JA</sub>	θ <sub>Jc</sub>	Unit
MSOP10	125	48	°C/W

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

### Electrical Characteristics

All test conditions: VDD = 3.3 V, data rate = 64 SPS, and FSR =  $\pm 2.048$  V, T<sub>A</sub> = -40 °C to 125 °C, unless otherwise noted.

Parameter	Test Conditions		Min	Typ	Max	Unit
Analog Inputs						
Common-mode Input Impedance	FSR = $\pm 6.144$ V <sup>(1)</sup>			1.3		MΩ
	FSR = $\pm 4.096$ V <sup>(1)</sup>			0.7		MΩ
	FSR = $\pm 2.048$ V			0.45		MΩ
	FSR = $\pm 1.024$ V			0.47		MΩ
	FSR = $\pm 0.512$ V			0.26		MΩ
	FSR = $\pm 0.256$ V			0.25		MΩ
Differential Input Impedance	FSR = $\pm 6.144$ V <sup>(1)</sup>			0.59		MΩ
	FSR = $\pm 4.096$ V <sup>(1)</sup>			0.33		MΩ
	FSR = $\pm 2.048$ V			0.18		MΩ
	FSR = $\pm 1.024$ V			0.10		MΩ
	FSR = $\pm 0.512$ V			0.07		MΩ
	FSR = $\pm 0.256$ V			0.07		MΩ
System Performance						
Resolution	NO missing code		16			Bits
DR	Data rate		64, 128, 256, 512, 1024, 2000, 4000, 8000			SPS
	Data rate variation	All data rates	– 10%		10%	
INL	Integral nonlinearity	DR = 1024 SPS, FSR = $\pm 2.048$ V		$\pm 0.6$	$\pm 1$	LSB
Offset Error	FSR = $\pm 2.048$ V, differential inputs			$\pm 1$	$\pm 3.2$	LSB
Offset Drift	FSR = $\pm 2.048$ V			0.01		LSB/°C
Offset Power-supply Rejection	FSR = $\pm 2.048$ V, DC supply variation			6		LSB/V
Offset Channel Match	Match between any two inputs			0.7		LSB
Gain Error	FSR = $\pm 2.048$ V, T <sub>A</sub> = –40 °C to 125 °C			0.05%	$\pm 0.25\%$	
Gain Drift <sup>(2)</sup>	FSR = $\pm 0.256$ V			3.7		ppm/°C
	FSR = $\pm 2.048$ V			3.7	10	ppm/°C
	FSR = $\pm 6.144$ V <sup>(1)</sup>			3.7		ppm/°C
	Gain power-supply rejection			78		dB
Gain Match	Match between any two gains			0.05%	0.10%	
Gain Channel Match	Match between any two inputs			0.01%	0.10%	
CMRR	Common-mode rejection ratio	At DC, FSR = $\pm 0.256$ V		126		dB
		At DC, FSR = $\pm 2.048$ V		115		dB

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

Parameter	Test Conditions		Min	Typ	Max	Unit
		At DC, FSR = ±6.144 V <sup>(1)</sup>		108		dB
		f <sub>CM</sub> = 50 Hz, DR = 1 kSPS		114		dB
		f <sub>CM</sub> = 60 Hz, DR = 1 kSPS		113		dB
Temperature Sensor						
Temperature Range			−40		125	°C
Temperature Resolution	14-bit			0.03125		
Accuracy	T <sub>A</sub> = −40°C to 125°C			±3		°C
	vs supply			±1		°C/V
Digital Input/Outputs						
V <sub>IH</sub>	High-level input voltage		0.7 x VDD		VDD	V
V <sub>IL</sub>	Low-level input voltage		GND		0.2 x VDD	V
I <sub>H</sub>	Input leakage, high	V <sub>IH</sub> = 5.5 V	−10		10	μA
I <sub>L</sub>	Input leakage, low	V <sub>IL</sub> = GND	−10		10	μA
Digital Output						
V <sub>OH</sub>	I <sub>SOURCE</sub> = 1 mA		0.8 x VDD			V
V <sub>OL</sub>	I <sub>SINK</sub> = 1 mA		GND		0.2 x VDD	V
Power Supply						
I <sub>VDD</sub>	Supply current	Power-down, T <sub>A</sub> = 25°C		4.6	7	μA
		Power-down		5.3	10	μA
		Operating, T <sub>A</sub> = 25°C		4.2	5	mA
		Operating		4.2	5.5	mA
P <sub>D</sub>	Power dissipation	VDD = 3.3 V		14	20	mW
Temperature Range	Specified performance		−40		+125	°C

(1) This parameter expresses the full-scale range of the ADC scaling. No more than  $V_{DD} + 0.3$  V or 5.5 V (whichever is smaller) must be applied to this device.

(2) Maximum value specified by characterization.

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

### Timing Specifications <sup>(1)</sup>

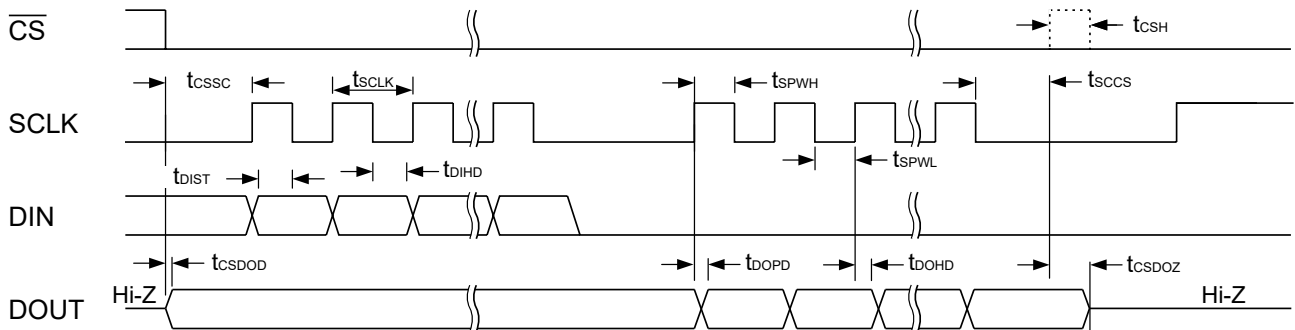
All test conditions: VDD = 2.7 V to 5.5 V and T<sub>A</sub> = -40 °C to 125 °C, unless otherwise noted.

**Table 2. Serial Interface**

Parameter	Description	Min	Typ	Max	Unit
t <sub>CSSC</sub>	Delay time, $\overline{CS}$ falling edge to first SCLK rising edge <sup>(1)</sup>	100			ns
t <sub>SCCS</sub>	Delay time, final SCLK falling edge to $\overline{CS}$ rising edge	100			ns
t <sub>CSH</sub>	Pulse duration, $\overline{CS}$ high	200			ns
t <sub>SCLK</sub>	SCLK period	80			ns
t <sub>SPWH</sub>	Pulse duration, SCLK high	100			ns
t <sub>SPWL</sub>	Pulse duration, SCLK low <sup>(2)</sup>	100			ns
				30.8	ms
t <sub>DIST</sub>	Setup time, DIN valid before SCLK falling edge	20			ns
t <sub>DIHD</sub>	Hold time, DIN valid after SCLK falling edge		700	800	ns
t <sub>DOHD</sub>	Hold time, SCLK rising edge to DOUT invalid	200			ns

(1)  $\overline{CS}$  can be tied low permanently in case the serial bus is not shared with any other device.

(2) Holding SCLK low longer than 30.8 ms resets the SPI interface.



**Figure 1. Serial Interface Timing**

**Table 3. Switching Characteristics: Serial Interface**

Parameter	Description	Test Conditions	Min	Typ	Max	Unit
t <sub>CSDOD</sub>	Propagation delay time, $\overline{CS}$ falling edge to DOUT driven	DOUT load = 20 pF    100 kΩ to GND			100	ns
t <sub>DOPD</sub>	Propagation delay time, SCLK rising edge to valid new DOUT	DOUT load = 20 pF    100 kΩ to GND	0		50	ns
t <sub>CSDOZ</sub>	Propagation delay time, $\overline{CS}$ rising edge to DOUT high impedance	DOUT load = 20 pF    100 kΩ to GND			100	ns

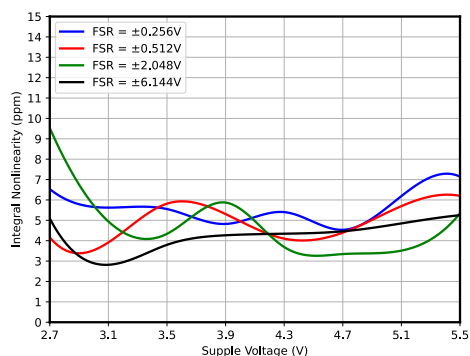
(1) Parameters are provided by design simulation.



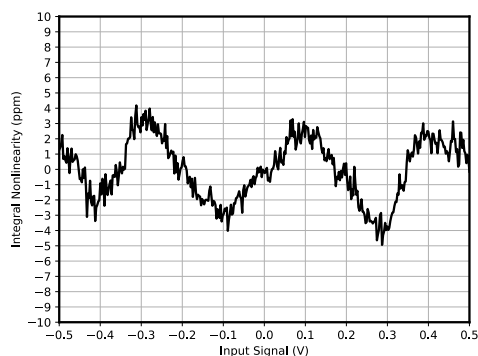
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## Typical Performance Characteristics

All test conditions:  $T_A = 25^\circ\text{C}$ ,  $V_{DD} = 3.3\text{ V}$ ,  $\text{FSR} = \pm 2.048\text{ V}$ ,  $\text{DR} = 64\text{ SPS}$  (unless otherwise noted).

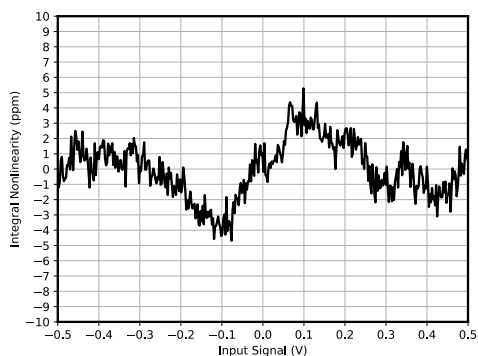


**Figure 2. INL vs. Supply Voltage**



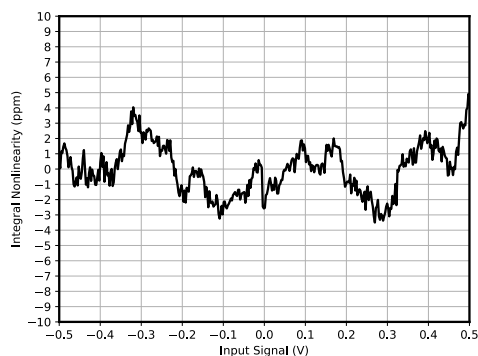
$V_{DD} = 3.3\text{ V}$ ,  $\text{FSR} = \pm 0.512\text{ V}$ ,  $\text{DR} = 64\text{ SPS}$ , best fit

**Figure 3. INL vs. Input Signal**



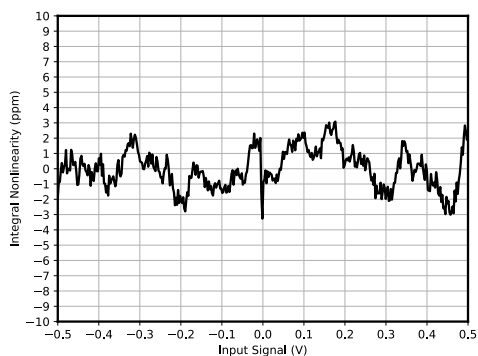
$V_{DD} = 5.0\text{ V}$ ,  $\text{FSR} = \pm 0.512\text{ V}$ ,  $\text{DR} = 64\text{ SPS}$ , best fit

**Figure 4. INL vs. Input Signal**



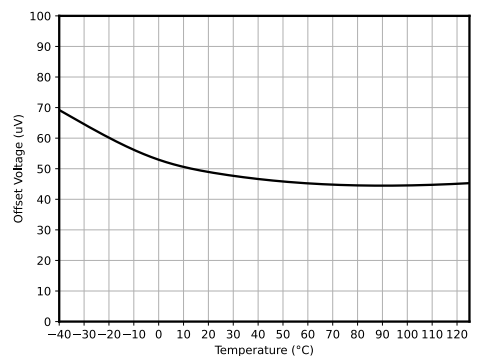
$V_{DD} = 3.3\text{ V}$ ,  $\text{FSR} = \pm 2.048\text{ V}$ ,  $\text{DR} = 64\text{ SPS}$ , best fit

**Figure 5. INL vs. Input Signal**



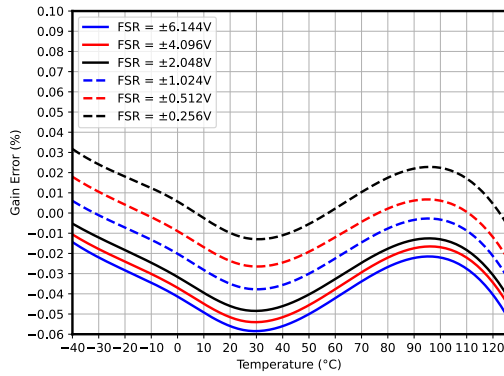
$V_{DD} = 5.0\text{ V}$ ,  $\text{FSR} = \pm 2.048\text{ V}$ ,  $\text{DR} = 64\text{ SPS}$ , best fit

**Figure 6. INL vs. Input Signal**

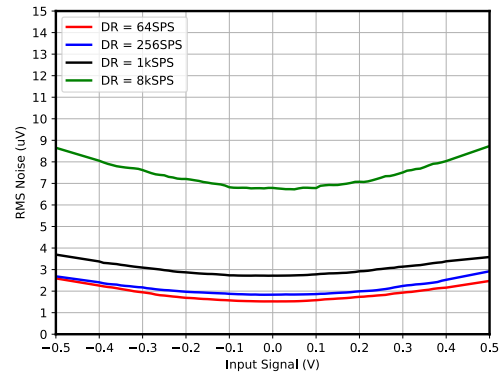


**Figure 7. Differential Offset Voltage vs. Temperature**

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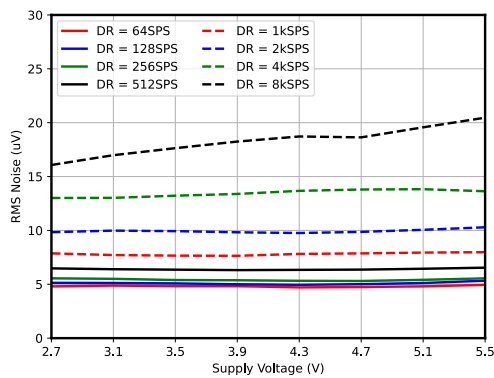


**Figure 8. Gain Error vs. Temperature**



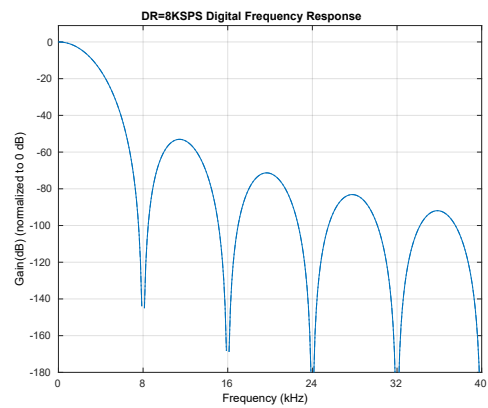
FSR =  $\pm 0.512$  V

**Figure 9. Noise vs. Input Signal**



FSR =  $\pm 0.512$  V

**Figure 10. Noise vs. Supply Voltage**



Provided by simulation results

**Figure 11. Digital Filter Frequency Response**

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

### Noise Performance

The Sigma-Delta ( $\Sigma\Delta$ ) ADC architecture operates based on oversampling principles. In this approach, the input signal is sampled at a high frequency, known as the modulator frequency. The sampled signal is then processed through filtering and decimation in the digital domain, resulting in the final conversion output at a specified data rate. The oversampling ratio (OSR), which is the ratio between the modulator frequency and the output data rate, plays a crucial role. By increasing the OSR, and consequently lowering the output data rate, the noise performance of the ADC can be optimized. This is achieved by averaging more samples of the internal modulator, thereby reducing input-referred noise. Additionally, increasing the gain proves beneficial for measuring low-level signals as it further contributes to the reduction of input-referred noise.

The following tables provide an overview of the noise performance of the device, with data representative of typical noise characteristics at a temperature of 25°C and the inputs externally shorted together. [Table 4](#) and [Table 5](#) display the input-referred noise in units of microvolts root mean square ( $\mu\text{VRMS}$ ), with microvolts peak-to-peak ( $\mu\text{VPP}$ ) values shown in parentheses. [Table 6](#) and [Table 7](#) present the corresponding data in terms of effective number of bits (ENOB), calculated from  $\mu\text{VRMS}$  values using [Equation 1](#). The noise-free bits, determined from peak-to-peak noise values using [Equation 2](#), are enclosed in parentheses.

$$\text{ENOB} = \ln(\text{FSR}/V_{\text{RMS}} - \text{Noise})/\ln(2) \quad (1)$$

$$\text{Noise - Free Bits} = \ln(\text{FSR}/V_{\text{PP}} - \text{Noise})/\ln(2) \quad (2)$$

**Table 4. Noise in  $\mu\text{VRMS}$  at VDD = 3.3 V**

Data Rate (SPS)	FSR (V)					
	$\pm 6.144$	$\pm 4.096$	$\pm 2.048$	$\pm 1.024$	$\pm 0.512$	$\pm 0.256$
64	187.5	125	62.5	31.25	15.62	7.81
128	187.5	125	62.5	31.25	15.62	7.81
256	187.5	125	62.5	31.25	15.62	7.81
512	187.5	125	62.5	31.25	15.62	7.81
1024	187.5	125	62.5	31.25	15.62	7.81
2k	187.5	125	62.5	31.25	15.62	7.81
4k	187.5	125	62.5	31.25	15.62	7.81
8k	187.5	125	62.5	31.25	15.62	7.81

**Table 5. Noise in  $\mu\text{VPP}$  at VDD = 3.3 V**

Data Rate (SPS)	FSR (V)					
	$\pm 6.144$	$\pm 4.096$	$\pm 2.048$	$\pm 1.024$	$\pm 0.512$	$\pm 0.256$
64	187.5	125	62.5	31.25	15.62	7.81
128	187.5	125	62.5	31.25	15.62	7.81
256	187.5	125	62.5	31.25	15.62	7.81
512	187.5	125	62.5	31.25	15.62	9.08
1024	187.5	125	62.5	31.25	15.62	11.52
2k	187.5	125	62.5	31.25	18.85	13.95
4k	226.19	146.29	75.74	40.42	24.64	18.98
8k	296.03	206.5	100.34	52.58	33.91	26.77

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Table 6. ENOB from RMS Noise at VDD = 3.3 V

Data Rate (SPS)	FSR					
	$\pm 6.144$	$\pm 4.096$	$\pm 2.048$	$\pm 1.024$	$\pm 0.512$	$\pm 0.256$
64	16	16	16	16	16	16
128	16	16	16	16	16	16
256	16	16	16	16	16	16
512	16	16	16	16	16	16
1024	16	16	16	16	16	16
2k	16	16	16	16	16	16
4k	16	16	16	16	16	16
8k	16	16	16	16	16	16

Table 7. Noise-Free Bits from Peak-to-Peak Noise at VDD = 3.3 V

Data Rate (SPS)	FSR					
	$\pm 6.144$	$\pm 4.096$	$\pm 2.048$	$\pm 1.024$	$\pm 0.512$	$\pm 0.256$
64	16	16	16	16	16	16
128	16	16	16	16	16	16
256	16	16	16	16	16	16
512	16	16	16	16	16	15.8
1024	16	16	16	16	16	15.4
2k	16	16	16	16	15.7	15.2
4k	15.7	15.8	15.7	15.6	15.3	14.7
8k	15.3	15.3	15.3	15.3	14.9	14.2

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

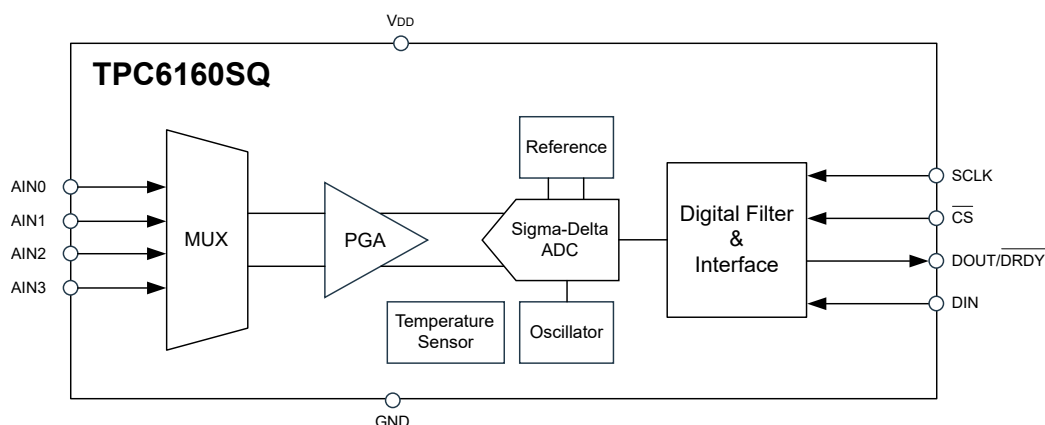
### Detailed Description

#### Overview

The TPC6160SQ is a compact, low-power, 16-bit sigma-delta analog-to-digital converter (ADC) designed to minimize external circuitry and enhance performance. It incorporates a  $\Sigma\Delta$  ADC core with adjustable gain, an internal voltage reference, a clock oscillator, and an SPI interface. Additionally, it integrates a precise temperature sensor. The ADC core measures a differential signal, VIN, representing the difference between V(AINP) and V(AINN). The core features a differential, switched-capacitor  $\Sigma\Delta$  modulator followed by a digital filter, providing strong common-mode signal attenuation.

The device operates in single-shot or continuous-conversion mode, with single-shot mode saving power by performing one conversion upon request and entering a power-down state. In continuous-conversion mode, the ADC automatically initiates conversions, and data can be read at any time, reflecting the most recent completed conversion.

#### Functional Block Diagram



**Figure 12. TPC6160SQ Block Diagram**

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

### Feature Description

#### Multiplexer

The TPC6160SQ is integrated with an input multiplexer (mux). It allows the measurement of either four single-ended signals or two differential signals. Also, the AIN0, AIN1, and AIN2 inputs can be differentially measured against AIN3. The configuration of the multiplexer is controlled by the MUX[2:0] bits in the Config register. In cases where single-ended signals are being measured, the negative input of the ADC is internally connected to GND through a switch within the multiplexer.

When single-ended inputs are being measured, the TPC6160SQ does not produce negative codes. Negative codes are indicative of negative differential signals, where  $(V_{(AINP)} - V_{(AINN)}) < 0$ . Electrostatic discharge (ESD) diodes to VDD and GND serve to protect the ADC inputs. The TPC6160SQ is allowed to measure absolute negative input voltage down to  $-128\text{ mV}$  and still needs to prevent the ESD diodes from turning on, it is essential to maintain the absolute voltage on any input within the range specified in the following equation:

$$\text{GND} - 0.3\text{ V} < V_{(AINx)} < \text{VDD} + 0.3\text{ V} \quad (3)$$

If there is a possibility that the voltages on the input pins may violate these conditions, it is advisable to employ external Schottky diodes and series resistors. This helps to limit the input current to safe values. Additionally, overdriving one unused input on the TPC6160SQ may impact conversions occurring on other input pins at that time. In cases where overdriving unused inputs is a possibility, it is recommended to clamp the signal using external Schottky diodes.

#### Analog Inputs

The TPC6160SQ employs a switched-capacitor input stage, where capacitors undergo a continuous charging and discharging process to measure the voltage between AIN<sub>P</sub> and AIN<sub>N</sub>. The equivalent resistance is determined by the values of the capacitors and the frequency at which they are switched.

The common-mode input impedance is determined by applying a common-mode signal to the shorted AIN<sub>P</sub> and AIN<sub>N</sub> inputs and measuring the average current consumed by each pin. The common-mode input impedance may vary depending on the selected full-scale range. The common-mode input impedance is denoted as  $Z_{CM}$ .

The differential input impedance is measured by applying a differential signal to the AIN<sub>P</sub> and AIN<sub>N</sub> inputs. The average current flowing through the input pins represents the differential current and scales with the selected full-scale range. The symbol  $Z_{DIFF}$  represents the differential input impedance.

Note that this unbuffered input path provides a dynamic load to the driving source. Therefore, resistor/capacitor combinations on the input pins can cause DC gain errors, depending on the output impedance of the source that is driving the ADC input. The table below shows the allowable external resistance/capacitance values such that no gain error at the 16-bit level is introduced when the data rate is within 2 kSPS.

**Table 8. External R-C Combination for No 16-Bit Gain Error**

R (Ω)	C (pF)
20	1000
50	400
100	200

#### Full-Scale Range (FSR) and LSB Size

The gain setting of PGA inside the TPC6160SQ  $\Sigma\Delta$  ADC determines the input full-scale range (FSR). The full-scale range is configured by bits PGA[2:0] in the Config register, and can be set to  $\pm 6.144\text{ V}$ ,  $\pm 4.096\text{ V}$ ,  $\pm 2.048\text{ V}$ ,  $\pm 1.024\text{ V}$ ,  $\pm 0.512\text{ V}$ , or  $\pm 0.256\text{ V}$ .

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

The table below presents the Full-Scale Range (FSR) alongside the corresponding Least Significant Bit (LSB) size. The LSB size is calculated from the full-scale voltage using the formula in Equation 4. It is essential to ensure that the analog input voltage never exceeds the specified analog input voltage range limit provided in the Electrical Characteristics. If a VDD greater than 4 V is utilized, the  $\pm 6.144$ -V full-scale range allows input voltages to extend up to the supply voltage. It is important to note that in such cases or whenever the supply voltage is less than the full-scale range (e.g., VDD = 3.3 V and full-scale range =  $\pm 4.096$  V), a full-scale ADC output code cannot be achieved, resulting in a loss of dynamic range.

$$\text{LSB} = \text{FSR}/2^{16} \quad (4)$$

**Table 9. Full-Scale Range and Corresponding LSB Size**

FSR	LSB Size
$\pm 6.144$ V <sup>(1)</sup>	187.5 $\mu$ V
$\pm 4.096$ V <sup>(1)</sup>	125 $\mu$ V
$\pm 2.048$ V	62.5 $\mu$ V
$\pm 1.024$ V	31.25 $\mu$ V
$\pm 0.512$ V	15.625 $\mu$ V
$\pm 0.256$ V	7.8125 $\mu$ V

(1) This parameter expresses the full-scale range of the ADC scaling. Do not apply more than VDD + 0.3 V to this device.

### Voltage Reference

The TPC6160SQ integrates an internal voltage reference, and the use of an external reference is not supported with this device. Any errors associated with the initial voltage reference accuracy and its drift with temperature are accounted for in the gain error and gain drift specifications provided in the specifications.

### Oscillator

The TPC6160SQ features an integrated oscillator, eliminating the need for an external clock to drive the device. It's important to note that the internal oscillator may exhibit drift over temperature and time. Additionally, the output data rate scales proportionally with the oscillator frequency.

### Temperature Sensor

The TPC6160SQ includes a precision temperature sensor, activated by setting TS\_MODE = 1 in the Config Register, which outputs a 14-bit left-justified result within a 16-bit conversion, with each LSB representing 0.03125°C and negative values in twos complement format.

Temperature (°C)	Digital Output (Binary)	HEX
128	01 0000 0000 0000	1000
127.96875	00 1111 1111 1111	0FFF
100	00 1100 1000 0000	0C80
75	00 1001 0110 0000	0960
50	00 0110 0100 0000	0640
25	00 0011 0010 0000	0320
0.25	00 0000 0000 1000	0008
0.03125	00 0000 0000 0001	0001
0	00 0000 0000 0000	0000

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Temperature (°C)	Digital Output (Binary)	HEX
–0.25	11 1111 1111 1000	3FF8
–25	11 1100 1110 0000	3CE0
–40	11 1011 0000 0000	3B00

**Converting from Temperature to Digital Codes**

For positive temperatures:

For positive temperature values, twos complement is not applied; instead, the number is directly converted to a 14-bit binary format, left-justified within the 16-bit result, with the MSB set to 0 to indicate a positive sign.

For negative temperatures:

To generate the two's complement of a negative number, first take the binary representation of its absolute value, complement all bits, add 1 to the result, and set the MSB to 1 to indicate the negative sign.

For positive temperature values, twos complement is not applied; instead, the number is directly converted to a 14-bit binary format, left-justified within the 16-bit result, with the MSB set to 0 to indicate a positive sign.

**Converting from Digital Codes to Temperature**

For positive temperatures:

For positive temperature values, twos complement is not applied; instead, the number is directly converted to a 14-bit binary format, left-justified within the 16-bit result, with the MSB set to 0 to indicate a positive sign.

For negative temperatures:

To generate the two's complement of a negative number, first take the binary representation of its absolute value, complement all bits, add 1 to the result, and set the MSB to 1 to indicate the negative sign.

For positive temperature values, twos complement is not applied; instead, the number is directly converted to a 14-bit binary format, left-justified within the 16-bit result, with the MSB set to 0 to indicate a positive sign.



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**Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with  
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**Digital Interface****Device Functional Modes****Reset and Power-Up**

When the TPC6160SQ powers up, the device undergoes a reset procedure that results in the configuration register (Config register) having all its bits set to their default values. In its default state, the device enters a power-down mode upon startup. During this mode, the interface of the device and digital blocks remain active, but no data conversions take place. This initial power-down state is designed to prevent systems with stringent power-supply requirements from experiencing a surge during the power-up phase.

**Operating Modes**

The TPC6160SQ operates in one of two modes: continuous-conversion or single-shot. The operating mode is determined by the state of the MODE bit in the Config register.

**Single-Shot Mode and Power-Down**

When the MODE bit in the Config register is set to 1, indicating single-shot mode, the TPC6160SQ enters a power-down state. This power-down state is the default state when power is first applied. While in this state, the device remains responsive to commands. The device stays in the power-down state until a 1 is written to the single-shot (SS) bit in the Config register. When the SS bit is set, the device powers up, resets the SS bit to 0, and initiates a single conversion. Once the conversion is completed, and the conversion data is ready, the device returns to the power-down state. Attempting to write a 1 to the SS bit while a conversion is already in progress has no effect. To switch to continuous-conversion mode, it is necessary to write a 0 to the MODE bit in the Config register.

**Continuous-Conversion Mode**

In continuous-conversion mode, where the MODE bit is set to 0, the TPC6160SQ consistently conducts conversions. Once a conversion is finished, the result is stored in the Conversion register, and the device promptly initiates another conversion. To transition to single-shot mode, one can write a 1 to the MODE bit in the Config register or perform a device reset.

**Duty Cycling for Low Power**

The noise performance of a  $\Sigma\Delta$  ADC typically improves at lower output data rates, as more samples of the internal modulator are averaged to produce a single conversion result. In scenarios where power consumption is critical consideration and enhanced noise performance at low data rates is not essential, the TPC6160SQ provides support for duty cycling. This feature enables significant power savings by periodically requesting high data-rate readings at an effectively lower data rate.

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### Programming Serial Interface

The SPI-compatible serial interface of the TPC6160SQ includes either four signals ( $\overline{CS}$ , SCLK, DIN, and DOUT/ $\overline{DRDY}$ ) or three signals (SCLK, DIN, and DOUT/ $\overline{DRDY}$  with  $\overline{CS}$  tied low). This interface facilitates tasks such as reading conversion data, accessing registers for reading and writing, and controlling the operation of the device.

### Chip Select

The chip select pin ( $\overline{CS}$ ) is utilized to select the TPC6160SQ for SPI communication, particularly beneficial in scenarios where multiple devices share the same serial bus. It is essential to keep  $\overline{CS}$  low throughout the serial communication process. When  $\overline{CS}$  is raised to a high state, the serial interface undergoes a reset, SCLK signals are disregarded, and DOUT/ $\overline{DRDY}$  enters a high-impedance state, rendering it unable to provide data-ready indication. For situations involving multiple devices where DOUT/ $\overline{DRDY}$  monitoring is necessary, periodically lowering  $\overline{CS}$  enables either an immediate high signal, indicating no new data, or an immediate low signal, indicating the availability of new data in the Conversion register. Data transfer can occur at any time without risking data corruption, as the current result is locked into the output shift register during transmission and remains unchanged until the communication concludes.

### Serial Clock

The serial clock pin (SCLK) incorporates a Schmitt-triggered input and serves the purpose of clocking data into and out of the TPC6160SQ through the DIN and DOUT/ $\overline{DRDY}$  pins. It is important to maintain a clean SCLK signal, despite the hysteresis present, to prevent glitches that can inadvertently shift the data. To initiate a reset of the serial interface, SCLK should be held low for 30.8 ms, and the subsequent SCLK pulse commences a new communication cycle. This time-out feature can be utilized to recover communication in cases where a serial interface transmission is interrupted. During idle periods of the serial interface, SCLK should be held low.

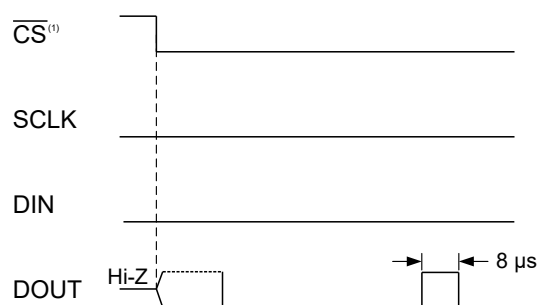
### Data Input

The data input pin (DIN) collaborates with SCLK to transmit data to the TPC6160SQ. Data is latched on the DIN pin at the falling edge of the SCLK signal. It's important to note that the device does not actively drive the DIN pin.

### Data Output and Data Ready

The data output and data ready pin (DOUT/ $\overline{DRDY}$ ) is employed, along with SCLK, for reading conversion and register data from the TPC6160SQ. Data present on DOUT/ $\overline{DRDY}$  is shifted out on the rising edge of the SCLK signal. Additionally, DOUT/ $\overline{DRDY}$  serves as an indicator of the completion of a conversion, signaling that new data is ready for retrieval. The pin transitions low when new data is available. DOUT/ $\overline{DRDY}$  can also be utilized to trigger a microcontroller to initiate the reading of data from the TPC6160SQ. In continuous-conversion mode, DOUT/ $\overline{DRDY}$  returns high again 8  $\mu$ s before the subsequent data ready signal (DOUT/ $\overline{DRDY}$  low) if no data is retrieved from the device. It is essential to complete the data transfer before DOUT/ $\overline{DRDY}$  returns high.

In single-shot mode, once the  $\overline{DRDY}$  is low for signaling data ready, the new SPI command should be sent 8  $\mu$ s after the  $\overline{DRDY}$  low.



(1)  $\overline{CS}$  can be held low if the TPC6160SQ does not share the serial bus with another device. If  $\overline{CS}$  is low, DOUT/ $\overline{DRDY}$  asserts low indicating new data is available.

**Figure 13. DOUT/ $\overline{DRDY}$  Behavior Without Data Retrieval in Continuous-Conversion Mode**

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

When the chip select ( $\overline{CS}$ ) pin is in a high state, the data output and data ready pin ( $DOUT/\overline{DRDY}$ ) is automatically configured with a weak internal pull-up resistor as a default setting. This configuration minimizes the chance of  $DOUT/\overline{DRDY}$  floating near the mid-supply voltage and causing leakage current in the master device. To deactivate this pullup resistor and place the device into a high-impedance state, set the `PULL_UP_EN` bit to 0 in the Config register.

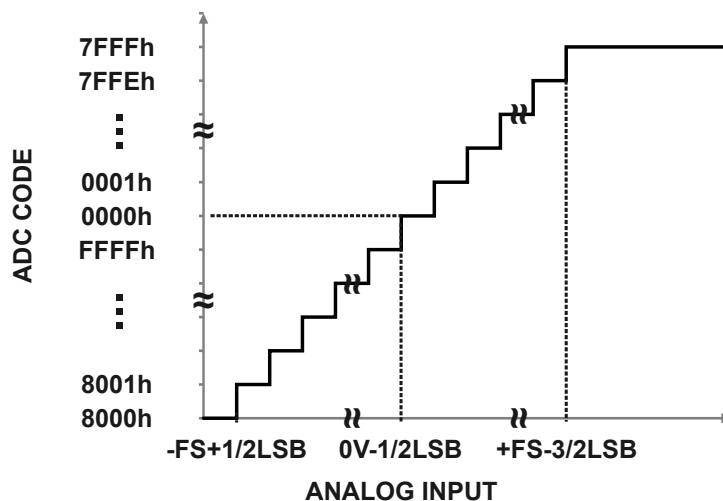
### Data Format

The TPC6160SQ outputs data in a 16-bit binary two's complement format. For a positive full-scale (+FS) input, the output code is 7FFFFh, while a negative full-scale (-FS) input results in an output code of 80000h. The output codes clip at these values for signals that exceed the full-scale range. The table below provides a summary of the ideal output codes corresponding to different input signals.

**Table 10. Input Signal versus Ideal Output Code**

Input Signal, VIN ( $A_{INP} - A_{INM}$ )	Ideal Output Code <sup>(1)</sup>
$\geq FS (2^{15} - 1) / 2^{15}$	7FFFh
$FS / 2^{15}$	0001h
0	0000h
$-FS / 2^{15}$	FFFFh
$\leq -FS$	8000h

(1) Excludes the effects of noise, INL, offset, and gain errors.



**Figure 14. Code Transition Diagram**

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

### Data Retrieval

Data is written to and read from the TPC6160SQ in the same manner for both single-shot and continuous conversion modes, without the need to issue specific commands. The operating mode for the device is determined by the MODE bit in the Config register.

To set the device in continuous-conversion mode, set the MODE bit to 0. In this mode, the device consistently initiates new conversions, even when the  $\overline{CS}$  is high.

To activate single-shot mode, set the MODE bit to 1. In this mode, a new conversion begins only when the SS bit is written with a value of 1.

The conversion data is continuously buffered and remains unchanged until new conversion data replaces it. Reading the data can be done at any time without the risk of corruption. When  $DOUT/\overline{DRDY}$  goes low, indicating the availability of new conversion data, the data can be read by shifting it out on  $DOUT/\overline{DRDY}$ . The most significant bit (MSB), bit 23, is clocked out on the first rising edge of SCLK. Simultaneously, new data for the Config register is latched on DIN during the falling edge of SCLK.

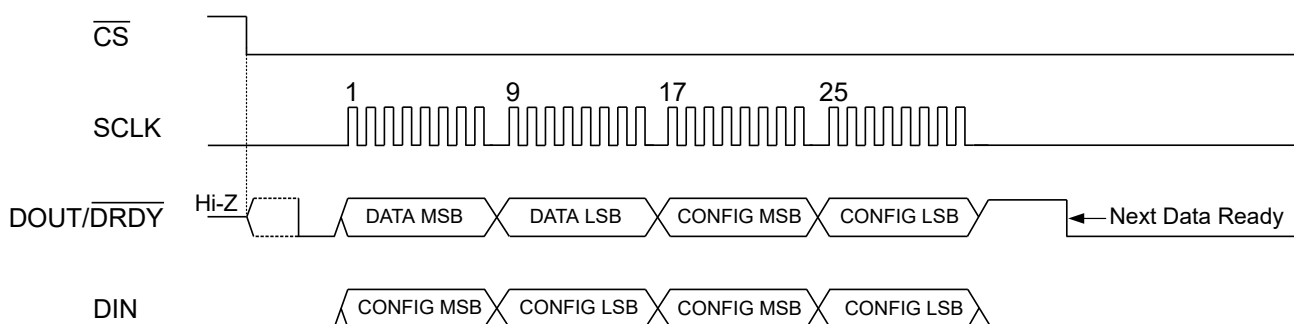
The TPC6160SQ provides an option for direct readback of the Config register settings within the same data transmission cycle. A complete data transmission cycle is either 48 bits (when the Config register readback is employed) or 16 bits (used only when the  $\overline{CS}$  line is controllable and not permanently tied low).

### 32-Bit Data Transmission Cycle

The data in a 32-bit data transmission cycle consists of six bytes: three bytes for the conversion result, and an additional three bytes for the Config register readback. The device always reads the MSB first.

During a single transmission cycle, write the same Config register setting twice, as illustrated in the figure below. For convenience, user can write the Config register setting once during the first half of the transmission cycle. Subsequently, maintain the DIN pin either low or high during the second half of the cycle. If there is no need to update the Config register, keep the DIN pin either low or high throughout the entire transmission cycle, while keeping the DIN pin high only in single-shot mode. The Config register setting written in the first three bytes of a 32-bit transmission cycle is read back in the last three bytes of the same cycle.

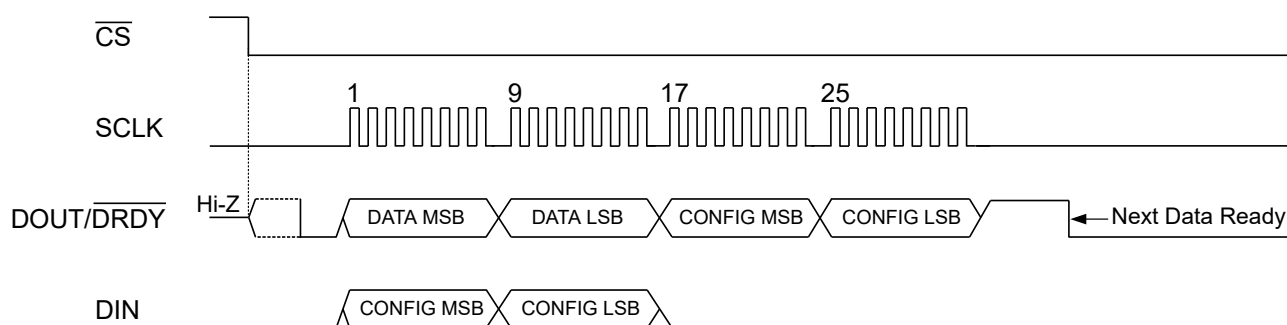
When utilizing a continuous SCLK for the entire 32-bit data transfer, ensure that the SCLK frequency remains below 1 MHz. In case an SCLK frequency exceeding 1 MHz is employed, introduce a delay between the transmission of the first 16 bits and the second 16 bits. This delay is necessary to allow for the complete decoding of the Config register write before initiating the readback of the Config register. Select a delay that ensures the time between the SCLK rising edge of the first bit and the SCLK rising edge of the 17th bit exceeds 16  $\mu$ s.



- (1)  $\overline{CS}$  can be held low if the TPC6160SQ does not share the serial bus with another device. If  $\overline{CS}$  is low,  $DOUT/\overline{DRDY}$  asserts low indicating new data is available.

**Figure 15. 32-Bit Data Transmission Cycle with Config Register Readback**

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor



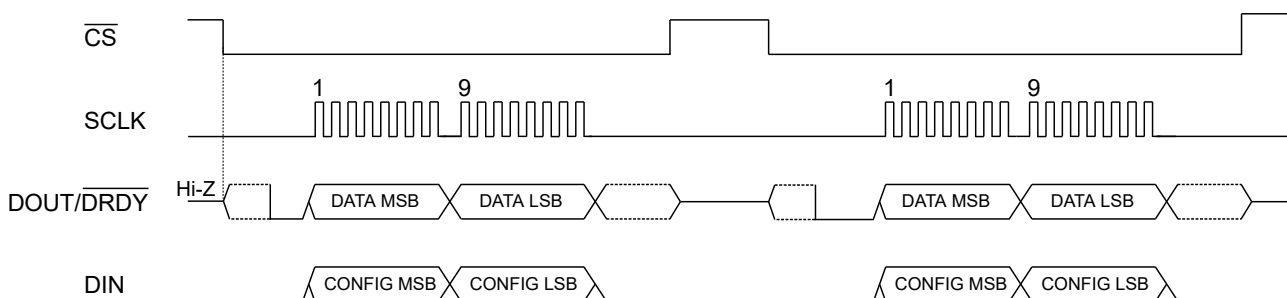
(1)  $\overline{CS}$  can be held low if the TPC6160SQ does not share the serial bus with another device. If  $\overline{CS}$  is low, DOUT/ $\overline{DRDY}$  asserts low indicating new data is available.

**Figure 16. 32-Bit Data Transmission Cycle: DIN Held Low**

### 16-Bit Data Transmission Cycle

If there is no need to read back the Config register data, the conversion data from the TPC6160SQ can be clocked out in a concise 16-bit data transmission cycle, as depicted in the figure below. After the 16th SCLK cycle, set  $\overline{CS}$  high to reset the SPI interface. Upon the subsequent lowering of  $\overline{CS}$ , data transmission initiates, starting with the currently buffered conversion result on the first SCLK rising edge. If DOUT/ $\overline{DRDY}$  is low at the beginning of data retrieval, the conversion buffer is already updated with a new result. Conversely, if DOUT/ $\overline{DRDY}$  is high, the same result from the preceding data transmission cycle is read.

If there is no need to update the Config register, keep the DIN pin either low or high throughout the entire transmission cycle in continuous-conversion mode, while keeping the DIN pin high only in single-shot mode.



(1)  $\overline{CS}$  can be held low if the TPC6160SQ does not share the serial bus with another device. If  $\overline{CS}$  is low, DOUT/ $\overline{DRDY}$  asserts low indicating new data is available.

**Figure 17. 16-Bit Data Transmission Cycle**

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### Register Summary

The TPC6160SQ features two accessible registers via SPI. The Conversion register is the result of the most recent conversion, while the Config register sets operating modes and inquiries about the status of the device.

#### Conversion Register [reset = 0000h]

The 16-bit Conversion register stores the results of the latest conversion in binary two's complement format. After power-up, the register is reset to 0 and retains this value until the initial conversion is finished. Refer to the table below for the register format.

**Table 11. Conversion Register**

15	14	13	12	11	10	9	8
D15	D14	D13	D12	D11	D10	D9	D8
R-0h	R-0h	R-0h	R-0h	R-0h	R-0h	R-0h	R-0h
7	6	5	4	3	2	1	0
D7	D6	D5	D4	D3	D2	D1	D0
R-0h	R-0h	R-0h	R-0h	R-0h	R-0h	R-0h	R-0h

LEGEND: R/W = Read/Write; R = Read only; -n = value after reset

**Table 12. Conversion Register Field Descriptions**

Bit	Field	Type	Reset	Description
15:0	D[15:0]	R	0000h	16-bit conversion result

#### Config Register [reset = 058Bh]

The 24-bit Config register can be configured to set the TPC6160SQ operating mode, input selection, data rate, full-scale range, temperature sensor mode, and global chop mode. The register format is shown in the table below.

**Table 13. Config Register**

15	14	13	12	11	10	9	8
SS	MUX[2:0]			PGA[2:0]			MODE
R/W-0h	R/W-0h			R/W-2h			R/W-1h
7	6	5	4	3	2	1	0
DR[2:0]			TS_MODE	PULL_UP_EN	NOP[1:0]		Reserved
R/W-4h			R/W-0h	R/W-1h	R/W-1h		R-1h

LEGEND: R/W = Read/Write; R = Read only; -n = value after reset

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Table 14. Config Register Field Descriptions

Bit	Field	Type	Reset	Description
15	SS	R/W	0h	<b>Single-shot conversion start</b> This bit is used to start a single conversion. SS can only be written when in power-down state and has no effect when a conversion is ongoing. When writing: 0 = No effect 1 = Start a single conversion (when in power-down state) Always read back as 0 (default).
14:12	MUX[2:0]	R/W	0h	<b>Input multiplexer configuration</b> These bits configure the input multiplexer. 000 = AIN <sub>P</sub> is AIN0 and AIN <sub>N</sub> is AIN1 (default) 001 = AIN <sub>P</sub> is AIN0 and AIN <sub>N</sub> is AIN3 010 = AIN <sub>P</sub> is AIN1 and AIN <sub>N</sub> is AIN3 011 = AIN <sub>P</sub> is AIN2 and AIN <sub>N</sub> is AIN3 100 = AIN <sub>P</sub> is AIN0 and AIN <sub>N</sub> is GND 101 = AIN <sub>P</sub> is AIN1 and AIN <sub>N</sub> is GND 110 = AIN <sub>P</sub> is AIN2 and AIN <sub>N</sub> is GND 111 = AIN <sub>P</sub> is AIN3 and AIN <sub>N</sub> is GND
11:9	PGA[2:0]	R/W	2h	<b>Programmable gain amplifier configuration</b> These bits configure the programmable gain amplifier. 000 = FSR is $\pm 6.144\text{ V}$ <sup>(1)</sup> 001 = FSR is $\pm 4.096\text{ V}$ <sup>(1)</sup> 010 = FSR is $\pm 2.048\text{ V}$ (default) 011 = FSR is $\pm 1.024\text{ V}$ 100 = FSR is $\pm 0.512\text{ V}$ 101 = FSR is $\pm 0.256\text{ V}$ 110 = FSR is $\pm 0.256\text{ V}$ 111 = FSR is $\pm 0.256\text{ V}$
8	MODE	R/W	1h	<b>Device operating mode</b> This bit controls the TPC6160SQ operating mode. 0 = Continuous-conversion mode 1 = Power-down and single-shot mode (default)
7:5	DR[2:0]	R/W	4h	<b>Data rate</b> These bits control the data-rate setting. 000 = 64 SPS 001 = 128 SPS 010 = 256 SPS 011 = 512 SPS 100 = 1024 SPS (default) 101 = 2 kSPS 110 = 4 kSPS 111 = 8 kSPS
4	TS_MODE	R/W	0h	<b>Temperature sensor mode</b>

## Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

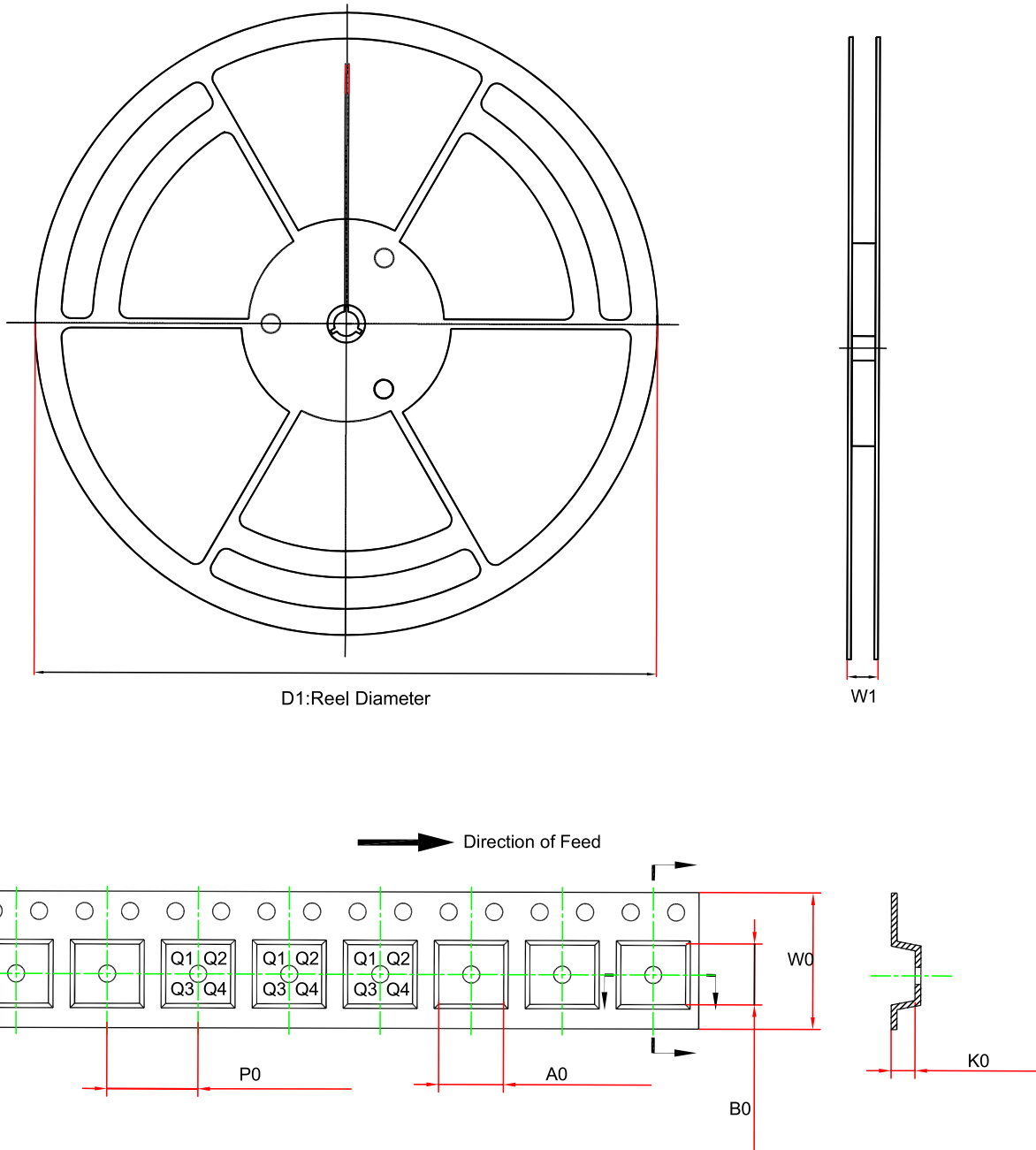
Bit	Field	Type	Reset	Description
				This bit configures the ADC to convert temperature or input signals. 0 = ADC mode (default) 1 = Temperature sensor mod
3	PULL_UP_EN	R/W	1h	<b>Pullup enable</b> This bit enables a weak internal pullup resistor on the DOUT/ $\overline{\text{DRDY}}$ pin only when $\overline{\text{CS}}$ is high. When enabled, an internal resistor connects the bus line to supply. When disabled, the DOUT/ $\overline{\text{DRDY}}$ pin floats. 0 = Pullup resistor disabled on DOUT/ $\overline{\text{DRDY}}$ pin 1 = Pullup resistor enabled on DOUT/ $\overline{\text{DRDY}}$ pin
2:1	NOP[1:0]	R/W	1h	<b>No operation</b> The NOP[1:0] bits control whether data are written to the Config register or not. For data to be written to the Config register, the NOP[1:0] bits must be 01. Any other value results in a NOP command. DIN can be held high or low during SCLK pulses without data being written to the Config register. 00 = Invalid data; do not update the contents of the Config register 01 = Valid data; update the Config register (default) 10 = Invalid data; do not update the contents of the Config register 11 = Invalid data; do not update the contents of the Config register
0	Reserved	R	1h	<b>Reserved</b> Writing either 0 or 1 to this bit has no effect. Always read back 1.

(1) This parameter expresses the full-scale range of the ADC scaling. Do not apply more than VDD + 0.3 V to this device.



**Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with  
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### Tape and Reel Information

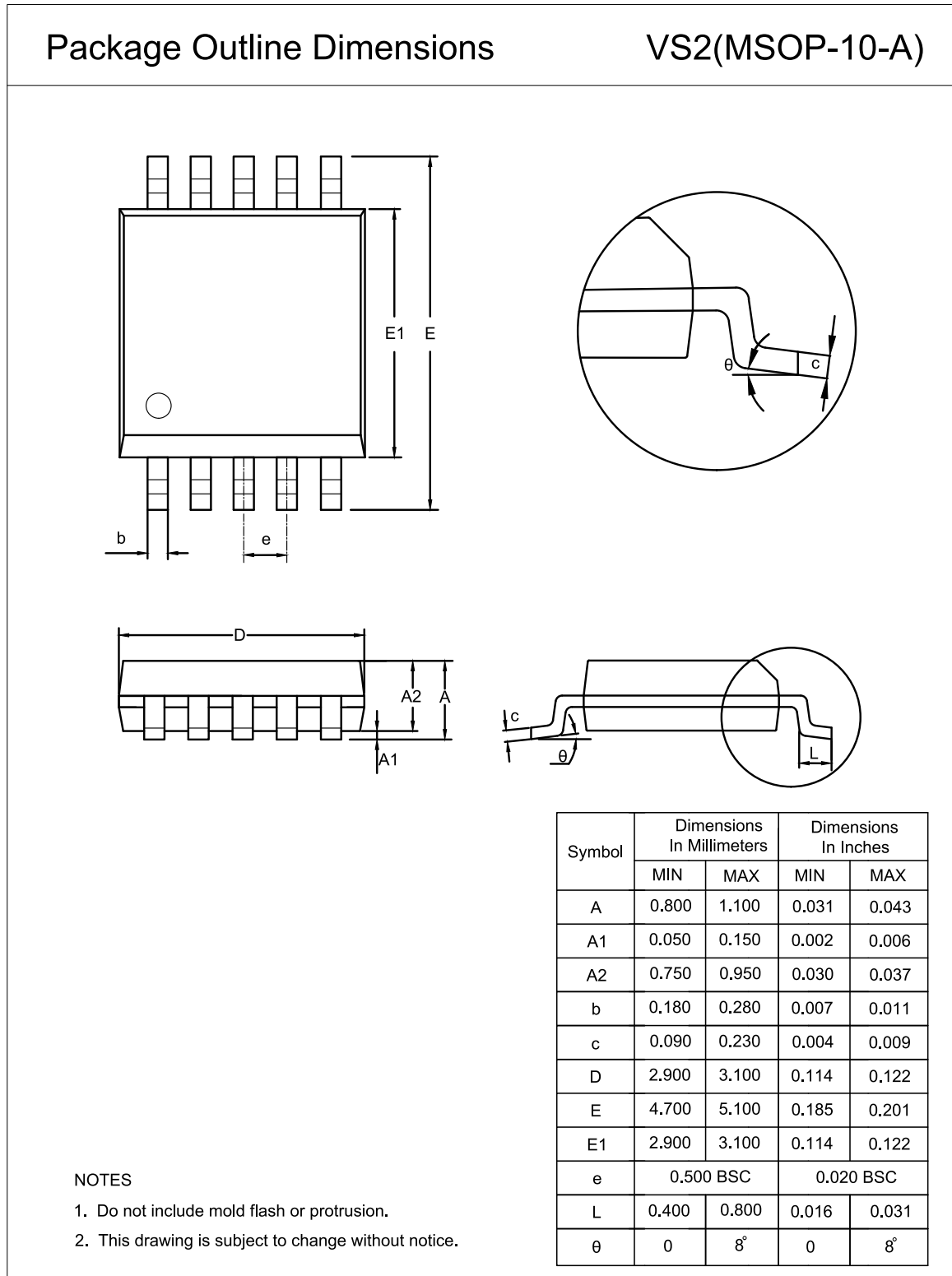


Order Number	Package	D1 (mm)	W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P0 (mm)	W0 (mm)	Pin1 Quadrant
TPC6160SQ-VS2R-S	MSOP10	330	17.6	5.3	3.4	1.4	8	12	Q1

# Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor

## Package Outline Dimensions

### MSOP10



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**Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with Internal Reference and Temperature Sensor****Order Information**

Order Number	Operating Temperature Range	Package	Marking Information	MSL	Transport Media, Quantity	Eco Plan
TPC6160SQ-VS2R-S	-40 to 125°C	MSOP-10	6160	2	T&R, 3000	Green

**Green:** 3PEAK defines "Green" to mean RoHS compatible and free of halogen substances.

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**Automotive, 16-bit, 8-kSPS, 4-channel Sigma-delta ADC with  
Internal Reference and Temperature Sensor****IMPORTANT NOTICE AND DISCLAIMER**

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