EXPLANATION OF ERROR SPECIFICIATIONS FOR ALLEGRO LINEAR HALL-EFFECT-BASED CURRENT SENSOR ICS AND TECHNIQUES FOR CALCULATING TOTAL SYSTEM ERROR

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ABSTRACT

Determining the accuracy of a system requires knowledge of the error introduced by each component. When looking at Allegro current sensor datasheets, the total error line item is a good approximation of the worst-case error seen in application. Every Allegro current sensor is tested in production to the total error limits. Total error includes offset and sensitivity error. Other error sources, such as nonlinearity, hysteresis, and ratiometry effects, are not included in the total error specification and should be included on a case-by-case basis. This application note will describe these error sources and their effect on the sensor output, using the ACS72981 device as an example.

INTRODUCTION

The ACS72981 is a low-noise, high-precision, linear Hall-effect sensor IC that is able to measure high-current signals directly on a PCB. The device is offered with a wide operating temperature range of –40°C to 150°C [1] with minimal error due to proprietary stress compensation techniques.

Housed in the small 7-pin PSOF package shown in Figure 1 (designated LR), the ACS72981 can measure high-current signals running directly on the PCB. The LR's internal conductor has a low resistance of only 200 μΩ resulting in ultra-low power loss and resistive heating. Current flowing through the internal conductor creates a magnetic field that is sensed by the differential Hall-effect elements on the die. The sensor outputs an analog voltage on pin 3 proportional to the sensed current.

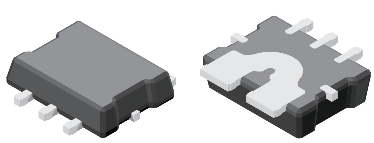

Figure 1: 7-pin PSOF package (suffix LR)

ACS72981 ERROR SOURCES

Moisture and Temperature

The ACS72981 is AEC-Q100 qualified and has no trouble operating in extreme environmental conditions. On-chip stress compensation techniques account for small shifts in sensitivity and offset due to changes in ambient temperature and humidity.

Sensitivity Drift Over Temperature

The ACS72981 has an analog output voltage proportional to the magnitude of the sensed input current I_{PR}. Sensitivity is measured as the change in output voltage in millivolts per ampere input (mV/A).

ACS72981 devices are programmed with temperature compensation information at the factory to correct for sensitivity drift. An end-of-line calibration step on the application board may further improve sensitivity accuracy.

Sensitivity error for the ACS72981 is specified within temperature ranges from –40°C to 25°C and from 25°C to 150°C. It is listed in the datasheet as Sensitivity Error and denoted with the symbol E_{sens}. Equation 1 shows the calculation used for sensitivity error where Sens is the sensitivity target from the datasheet and Measured Sensitivity is the sensitivity of the part.

Equation 1:

$$E_{SENS} = \left(\frac{Measured\ Sensitivity}{Sens} - 1 \right) \times 100\ (\%)$$

[1] All ACS72981 devices operate up to 150°C. Operating ranges for high-current devices are derated for expected resistive heating.

Sensitivity Linearity Error

Allegro current sensor datasheets specify sensitivity error at one current level, normally the maximum rated current. To account for changes in sensitivity over the full output range, the linearity error should be added to the sensitivity error. Allegro tests sensitivity linearity error at full-scale and half-scale of the rated input in production. This is specified as Nonlinearity in the ACS72981 datasheet and denoted by the symbol E_{LIN}.

To calculate linearity error, the ratio of sensitivity seen at full-scale and half-scale current is compared, as shown in Equation 2.

Equation 2:

$$E_{LIN} = \left(\frac{Sens_{IPR(FULL)}}{Sens_{IPR(HALF)}} - 1 \right) \times 100\ (\%)$$

Quiescent Voltage Output Drift Over Temperature

When no current is applied, the output of the Allegro current sensors will maintain a steady known voltage to indicate the absence of input. This Quiescent Voltage Output (QVO) is an offset in the output signal and used as the zero-amp point. The nominal QVO values for the two supply voltage levels and two directionalities of the device are shown in Table 1.

Table 1: Nominal QVO in Different Operating Modes

Supply Voltage	Directionality	Nominal QVO [2]
5 V	Unidirectional	0.500
	Bidirectional	2.500
3.3 V	Unidirectional	0.330
	Bidirectional	1.650

The ACS72981 and other high accuracy Allegro current sensor devices are programmed with temperature compensation information at the Allegro factory to stabilize the QVO output. If calibration at end of line is possible, the measured QVO can be stored in the system memory to be used for later calculations.

QVO error for the ACS72981 is specified within temperature ranges from –40°C to 25°C and from 25°C to 150°C. It is listed in the datasheet as Voltage Offset Error and denoted with the symbol V_{OE}. Equation 3 shows the calculation used for QVO error.

Equation 3:

$$V_{OE} = Measured\ QVO - QVO$$

Hysteresis

The ACS72981 has a non-ferrous copper leadframe that does not magnetize after sensing currents. The ACS772 and ACS773, along with previous generation CB packaged devices, have an internal magnetic concentrator that will magnetize slightly after current is applied to the device. The remnant field from the magnetized core will shift the QVO point as specified in the hysteresis line item in the characteristic table. This does not need to be considered for devices in SOIC or LR packages, such as the ACS72981.

Total Output Error

Total error is the difference between the measured and ideal voltage outputs referenced to output signal swing, as shown in Equation 4. Referencing the signal swing instead of V_{OUT} prevents the absolute voltage of the output from changing the result. Calculating total error as a percentage of the signal swing is useful at full scale, but the result of Equation 4 becomes misleading at low current inputs (I_P). As the output signal size becomes small (denominator), offset error in the numerator stays constant. This can create a situation where the error in amps is small but appears as a large percentage of the output signal. It is valuable to compare error in both amps and percent when calculating system accuracy.

Equation 4:

$$E_{TOT} = \left(\frac{V_{OUT} - V_{OUT_{IDEAL}}}{Sens_{ideal} \times I_P} \right) \times 100\ (\%)$$

The limits for total error are tighter than just the sum of offset and sensitivity error. This ensures a device does not leave the Allegro factory with both a high offset and high sensitivity error.

Lifetime Drift

In order to ensure robust lifetime performance, a subset of Allegro current sensors is stressed before release to simulate application conditions. Automotive-grade devices, such as the ACS72981, are qualified to the AEC-Q100 standard. The results of these stresses are used to specify lifetime drift numbers. The ACS72981 datasheet has line items for Sensitivity Error Including Lifetime, Total Error Including Lifetime, and Electric Offset Error Including Lifetime. These limits can be using in place of the values not including lifetime drift to take into account the effect of rigorous application stress.

[2] These will scale with supply voltage in accordance with operation outlined in the Ratiometric Performance section.

RATIOMETRY PERFORMANCE

The ACS72981 implements a ratiometric output that scales proportionally with supply voltage. This is intended to reduce the error at the output of an ADC that uses the supply voltage and ground of the device as references. In noisy systems with fluctuating ADC references, ratiometry will greatly improve the accuracy of the overall system.

Ratiometry is implemented on both QVO and sensitivity values. Figure 2 below shows the shift in offset and change in sensitivity as V_{CC} changes from 4.5 to 5.5 V on a 5 V device [3].

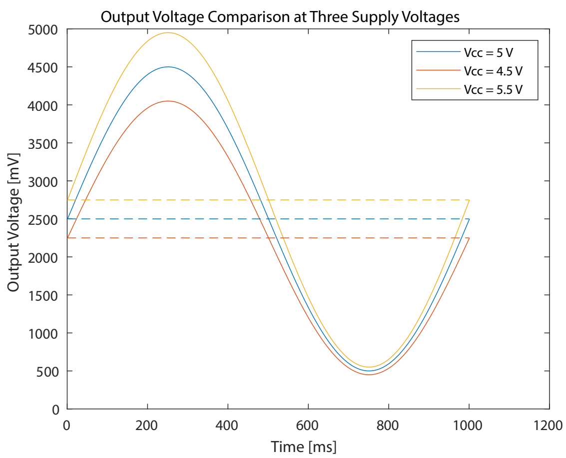

Figure 2: Ratiometric Output Operation of the ACS72981LLRATR-50B5 at Different Supply Voltages

To better illustrate the changes in QVO and sensitivity across the supply voltage range, Figure 3 plots them side by side.

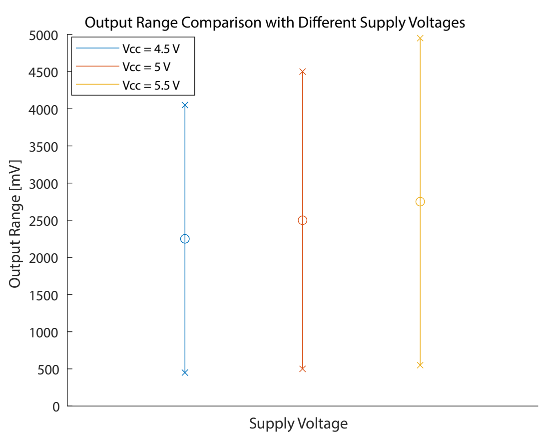

Figure 3: Output Range of Ratiometric Operation at Different Supply Voltages

Consider a system comprised of an ACS72981, an ADC, and a processor. A single supply voltage is used for the current sensor and the ADC reference. The output of the ACS72981 is fed into the ADC, and the output of the ADC is read by the processor. The processor will rely on the output of the ADC for information on the sensed current. Any influence from variations in the supply voltage will add error to the measurement. The ratiometric performance of the ACS72981 scales the output of the sensor at the same rate as the expanding ADC range. Equation 5 through Equation 9 demonstrate how the relationship of current to output code in this system is independent of supply voltage so that no error is induced by changing supply voltage.

Equation 5:

$$QVO_{Vcc} = QVO_{5V} \times \frac{V_{CC}}{5\text{ V}}$$

Equation 6:

$$Sens_{Vcc} = Sens_{5V} \times \frac{V_{CC}}{5\text{ V}}$$

Equation 5 and Equation 6 show the ratiometric scaling that the ACS72981 is performing internally. Both QVO and the sensitivity level scale proportionally with the voltage supply level.

Equation 7 sums these to show the output of the ACS72981 with respect to the ratiometrically scaled values for sensitivity and offset.

Equation 7:

$$V_{out} = QVO_{Vcc} + Sens_{Vcc} \times Current$$

The general equation for the output code of the ADC is shown in Equation 8 and does depend upon the instantaneous value of its reference V_{CC}. Once the V_{OUT} of the ACS72981 is referenced back to the 5 V values of QVO and sensitivity, the V_{CC} dependency cancels out.

Equation 8:

$$ADC_{code} = \frac{V_{OUT}}{V_{CC}} \times 2^{\text{Bit}}$$

Equation 9 shows that ratiometric operation works as intended. The microprocessor can convert the ADC output to input current using only the ideal values and does not need information on the supply voltage to do so accurately.

Equation 9:

$$ADC_{code} = \frac{(QVO_{5V} + Sens_{5V} \times Current)}{5\text{ V}} \times 2^{\text{Bit}}$$

[3] Following ratiometric examples use 5 V as the nominal supply voltage. These are valid for 3.3 V nominal as well.

Ratiometry Error Sources

The ACS72981 has very accurate ratiometry performance to ensure that the above relationships hold true across the operational supply voltage range. While the supply voltage is within 4.5 to 5.5 V, QVO will only vary ±3.5 mV and sensitivity 0.6% from the expected scaled value. However, it is not immediately clear what impact the ratiometry error has on the accuracy of the sensor.

If V_{CC} is 1% low, the device sensitivity also shifts 1% down to accommodate the ADC's lowered operating range. This tracking has a tolerance, which is covered by the Sens Ratiometry Error specification in the datasheet and denoted with the symbol $Rat_{ERRSens}$. Perfect ratiometry performance would scale the sensitivity at the same rate as V_{CC}. Equation 10 calculates sensitivity ratiometry error for a 5 V device. When sensitivity and V_{CC} scale by the same amount, the fraction within the brackets is 1 and sensitivity ratiometry error is 0%.

Equation 10:

$$Rat_{ERRSens} = \left(\frac{\dfrac{Sens_{Vcc}}{Sens_{5V}}}{\dfrac{V_{CC}}{5\text{ V}}} - 1 \right) \times 100\ (\%)$$

The same relationship holds for QVO and is covered by the QVO Ratiometry Error specification in the datasheet and denoted with the symbol $V_{RatERRQVO}$. This error is calculated in mV as the difference between the ideal QVO and the measured output voltage, as shown in Equation 11.

Equation 11:

$$V_{RatERRQVO} = \left[QVO_{Vcc} - \left(QVO_{5V} \times \frac{V_{CC}}{5\text{ V}} \right) \right]$$

Ratiometry Error Effect on Output

Accounting for ratiometry error complicates the relationship between applied current and ADC output. $V_{RatERRQVO}$ is specified in mV and is added as error directly to QVO_{Vcc} as shown in Equation 12.

Equation 12:

$$QVO_{Vcc} = QVO_{5V} \times \frac{V_{CC}}{5\text{ V}} + V_{RatERRQVO}$$

Equation 13:

$$Sens_{Vcc} = Sens_{5V} \times \frac{V_{CC}}{5\text{ V}} \times \left(1 + \frac{Rat_{ERRSens}}{100} \right)$$

Equation 13 shows the effect of ratiometry error on the nominal sensitivity. Because $Rat_{ERRSens}$ is a percent error of the ratiometric scaling, it must be added to 1 and multiplied.

Equation 14:

$$ADC_{code} = \left[\frac{QVO_{5V} + Sens_{5V} \times Current \times \left(1 + \dfrac{Rat_{ERRSens}}{100} \right)}{5\text{ V}} + \frac{V_{RatERRQVO}}{V_{CC}} \right] \times 2^{\text{Bit}}$$

The ADC output remains dependent on V_{CC} due to the way $V_{RatERRQVO}$ is specified. Equation 14 shows the new calculation for ADC code taking ratiometry error into consideration.

Equation 15:

$$V_{error} = V_{RatERRQVO} \times \frac{5\text{ V}}{V_{CC}} + Sens_{5V} \times Current \times Rat_{ERRSens}$$

Converting the ADC code with ratiometry error into an output voltage and subtracting the ideal output results in an output error in volts. Equation 15 can be used to calculate the voltage output error that results from errors in ratiometry. To calculate the error in amps, Equation 15 needs to be divided by the ideal sensitivity.

CALCULATING SYSTEM ACCURACY

Depending on the conditions of the end application, it is possible that some of the sources of error listed above will not have an impact on total system accuracy.

Temperature Drift (QVO and Sens): The ACS72981 has three accuracy ranges for QVO and sensitivity; One specified at 25°C, one from 25°C to 150°C, and one from 25°C to –40°C. In general, the accuracy limits at colder temperatures are wider or match the performance at hot temperatures. If the ambient temperature of the end application is known, the relevant limits can be chosen from the characteristic table.

Linearity (Sens): Linearity error should be considered if the end application is monitoring current throughout the full range of I_P. If only a limited range of the output is being monitored, an AC peak or DC current value for example, linearity will not affect the accuracy of the system.

Ratiometry Error (QVO and Sens): If the end application has a precision voltage supply, the ACS72981 will not be operating ratiometrically. In this case, the error of ratiometric operation will not influence the accuracy of the system.

Example Calculations

Consider an example application where the voltage supply to the device is stable, and the application is for a DC current at the maximum rated I_P. In this case, linearity error and ratiometry error can be ignored. Using a sum of squares average, Table 2 shows that the total error for the system should only be slightly higher than the sensitivity error of the device.

Table 2: Application Example 1 Error Estimation

	Error Source	Error	Units
Offset Voltage	Offset Error	±10	mV
		0.5	%
	Offset Ratiometry Error	0	mV
		0	%
Sensitivity Error	Sensitivity Error	3.75	%
	Sensitivity Ratiometry	0	%
	Linearity Error	0	%
Total Error	Sum of Squares Calculation	3.78	%

A second example calculation is shown in Table 3. In this application, the supply voltage can fluctuate within the operating range of the device, so ratiometry errors are included. The system is also monitoring current throughout the whole range of I_P and cannot disregard linearity error. Again, the total error of the system is dominated by sensitivity error, with other error sources increasing the total error of the system by only 0.13%.

Table 3: Application Example 2 Error Estimation

	Error Source	Error	Units
Offset Voltage	Offset Error	±10	mV
		0.5	%
	Offset Ratiometry Error	3.5	mV
		0.175	%
Sensitivity Error	Sensitivity Error	3.75	%
	Sensitivity Ratiometry	0.6	%
	Linearity Error	0.8	%
Total Error	Sum of Squares Calculation	3.91	%

CONCLUSION

Understanding the test conditions and error specifications of Allegro currents is important to correctly predict the accuracy of the overall system. An analysis should be performed for each application to determine the operating conditions and which error sources will impact the accuracy of the device. In general, the sensitivity error limit is a close approximation for the statistical average error of an Allegro current sensor.

Revision History

Number	Date	Description	Responsibility
–	April 8, 2020	Initial release	M. McNally