Application Note

Linear Hall-Effect Sensor Angle Measurement Theory, Implementation, and Calibration

Mitch Morse *Current and Magnetic Sensing*

ABSTRACT

This application note discusses how two one-dimensional linear Hall-effect sensors can be used to measure 2D angles, including both limited-angle and 360° rotation measurements. This document provides details on some calibrated and uncalibrated implementations to help meet angle measurement accuracy requirements. This report also covers the number of sensors needed, and the preferred magnet types for each method. For details on how one 3D linear Hall-effect sensor can be used to measure 2D angles, see the *Angle Measurement With Multi-Axis Linear Hall-Effect Sensors* application report.

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Trademarks

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1 Introduction

Linear Hall effect sensors measure the strength of a magnetic field and output a voltage proportional to that measurement. Based on the degree range and resolution needed, one or more linear Hall sensors can be used to determine the magnet direction. This application report covers angle measurements using no calibration, peak calibration, lookup table calibration, and a hybrid method of both the peak calibrated and lookup table methods.

2 Overview

2.1 Types of Magnetization

The two main types of magnetization in permanent magnets are axial and diametric. This terminology makes most sense when talking about discs, cylinders, and ring magnets. Axial magnets have north and south poles that are on the flat surfaces of the magnet. Diametric magnets have north and south poles that are on the rounded edges of the magnet.

Some examples of axially magnetized magnets are the two left magnets in Figure 2-1 and the two left magnets in Figure 2-2.

Some examples of diametrically magnetized magnets are the two right magnets in Figure 2-1 and the two right magnets in Figure 2-2.

Other magnet types are typically referred by shape, such as block and sphere magnets (Figure 2-3 and Figure 2-4), or by unique polarity, for example a multipole ring magnet (Figure 2-5).

2.2 Types of Magnets

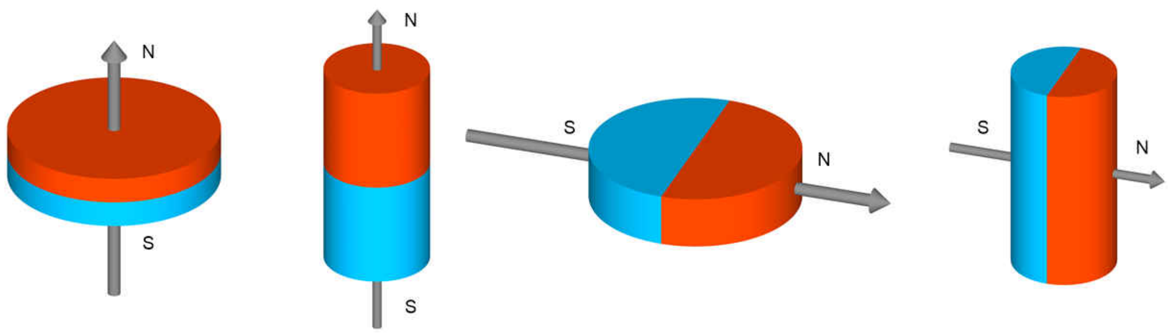

Figure 2-1. Disc and Cylinder Magnets

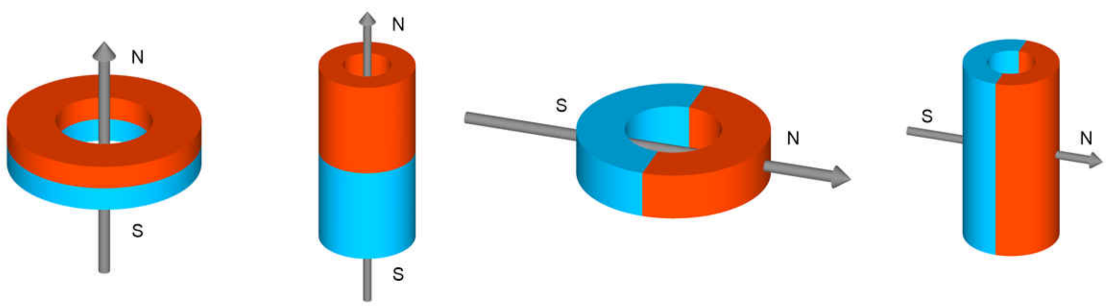

Figure 2-2. Ring Magnets

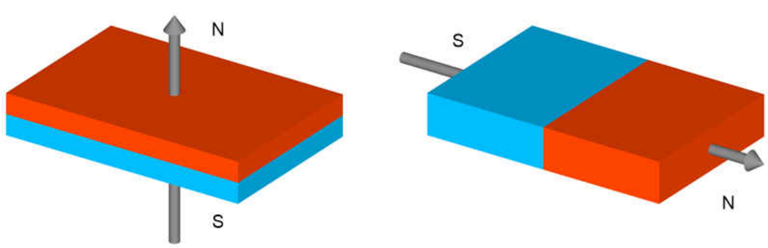

Figure 2-3. Block Magnets

Figure 2-4. Sphere Magnet

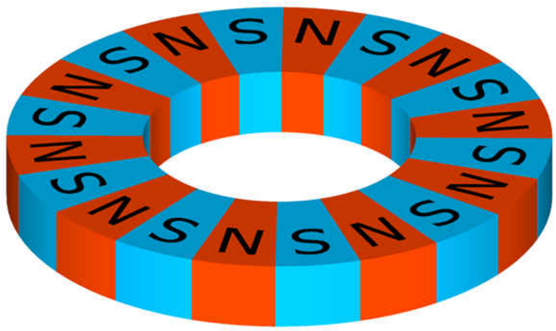

Figure 2-5. Multipole Ring Magnet

3 Device Descriptions

When using linear Hall effect sensors to measure angles, a bipolar sensor is generally most practical to use, although unipolar sensors can still be used for limited-angle measurements. Bipolar sensors respond to both the north and south poles of a magnet, and allow for wider-angle measurements. Unipolar sensors respond to one pole of the magnet allowing for only half of the movement range. The following subsections list some of the linear Hall effect devices from TI.

3.1 2.5-V to 38-V, Bipolar Hall Effect Sensor Family: DRV5053 and DRV5053-Q1

The DRV5053 is a chopper-stabilized Hall effect sensor that offers a magnetic sensing solution with superior sensitivity stability over temperature and integrated protection features.

The 0-V to 2-V analog output responds linearly to the applied magnetic flux density, and distinguishes the polarity of magnetic field direction. A wide operating voltage range of 2.5 V to 38 V with reverse polarity protection up to –22 V makes this device suitable for a wide range of industrial and consumer applications.

Internal protection functions are provided for reverse-supply conditions, load dump, and output short circuit or overcurrent.

The DRV5053-Q1 is the automotive-grade version of the DRV5053.

3.2 High-Accuracy, 3.3-V or 5-V, Ratiometric, Bipolar Hall Effect Sensor Family: DRV5055 and DRV5055-Q1

The DRV5055 is a linear Hall effect sensor that responds proportionally to magnetic flux density. This device can be used for accurate position sensing in a wide range of applications.

The device operates from 3.3-V or 5-V power supplies. When no magnetic field is present, the analog output drives half of VCC. The output changes linearly with the applied magnetic flux density, and four sensitivity options enable maximal output voltage swing based on the required sensing range. North and south magnetic poles produce unique voltages.

Magnetic flux perpendicular to the top of the package is sensed, and the two package options provide different sensing directions.

The device uses a ratiometric architecture that can eliminate error from VCC tolerance when the external analog-to-digital converter (ADC) uses the same VCC as a reference. Additionally, the device features magnet temperature compensation to counteract magnet drift for linear performance across a wide –40°C to +125°C temperature range.

The DRV5055-Q1 is the automotive-grade version of the DRV5055.

3.3 High-Accuracy, 3.3-V or 5-V, Ratiometric, Unipolar Hall Effect Sensor Family: DRV5056 and DRV5056-Q1

The DRV5056 is a linear Hall effect sensor that responds proportionally to flux density of a magnetic south pole. The device can be used for accurate position sensing in a wide range of applications.

The devices features a unipolar magnetic response. The analog output drives 0.6 V when no magnetic field is present, and increases when a south magnetic pole is applied. This response maximizes the output dynamic range in applications that sense one magnetic pole. Four sensitivity options further maximize the output swing based on the required sensing range.

The device operates from 3.3-V or 5-V power supplies. Magnetic flux perpendicular to the top of the package is sensed, and the two package options provide different sensing directions.

The device uses a ratiometric architecture that minimizes error from the VCC tolerance when the external analog-to-digital converter (ADC) uses the same VCC as a reference. Additionally, the device features magnet temperature compensation to counteract magnet drift for linear performance across a wide –40°C to +125°C temperature range.

The DRV5056-Q1 is the automotive-grade version of the DRV5056.

4 Methods

Table 4-1 shows a summary of the angle measurement methods discussed in this application report. For the column labeled *Magnet Placement Orientation Required?*, the term *Approximately* means that the magnet must be oriented during placement, but not very precisely. For more information about each method, see the associated sections linked in Table 4-1.

Note

When trying to achieve high accuracy and resolution with 360° rotation, the *Peak + Lookup Hybrid* method is easier to implement than the standard lookup table. The *Peak + Lookup Hybrid* method is used for the DRV5055-ANGLE-EVM.

Table 4-1. Angle Measurement Summary

Calibration Method	Recommended Magnet Options	Magnet Placement Orientation Required?		Accuracy Improved by Adding:	# Sensors Needed		Estimated Accuracy Peak-to-Peak Error (Based on measured data with a DRV5055)	Complexity
		1 Sensor	2+ Sensors		< 180°	360°		
Uncalibrated	Diametrically magnetized disc or axially magnetized cylinder or block	Yes	Yes	Sensors	1+	2+	= 180° / #Sensors	Low
Peak Calibrated	Diametrically magnetized disc	Yes	Yes	N/A	1	2	≈ 8°	Low
Lookup Table	Diametrically magnetized disc	Approximately	No	Calibration points	1	2	≈ (Spacing Between Cal Points) / 8	High
Peak + Lookup Hybrid	Diametrically magnetized disc	Approximately	No	Calibration points	1	2	≈ (Spacing Between Cal Points) / 15	Medium

4.1 Uncalibrated Implementations

4.1.1 Overview

4.1.1.1 General Implementation

The peak amplitude of the signal is unknown with an uncalibrated system. Therefore, the only usable information from the sensor is whether V_{OUT} is greater or less than V_{VCC} / 2, as shown in Figure 4-1. This information indicates whether the magnet is pointing towards a degree range (or region) where the sensor is sensing more north or more south polarity. The number of regions for a system depends on the number of sensors used.

Figure 4-1. Uncalibrated Sensor Positions

4.1.1.2 Preferred Magnet Types

- Diametrically magnetized disc or cylinder
- Axially magnetized cylinder
- Block magnet

4.1.1.3 General Accuracy and Resolution

- Low accuracy
- Low resolution
- Results come in the form of general regions
- Accuracy can be improved by adding sensors

4.1.1.4 Considerations

- The magnet must be oriented to align desired regions.
- The boundary line for each sensor is at V_{OUT} = V_{VCC} / 2. If V_{VCC} / 2 is measured, then either side of the boundary line may be chosen as the measured region.
- The uncalibrated implementations discussed here are for 360° rotation. For smaller ranges of movement, fewer regions are available.

4.1.2 One Bipolar Sensor, Uncalibrated

4.1.2.1 Specific Implementation

With one sensor, as shown in Figure 4-2, the sensor output voltage takes the form shown in Figure 4-3. Because there is no calibration phase, the peak amplitude is unknown.

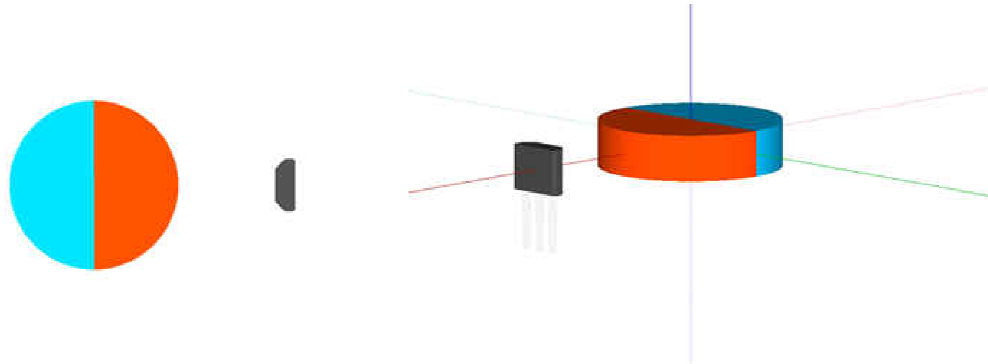

Figure 4-2. One Sensor Near Magnet

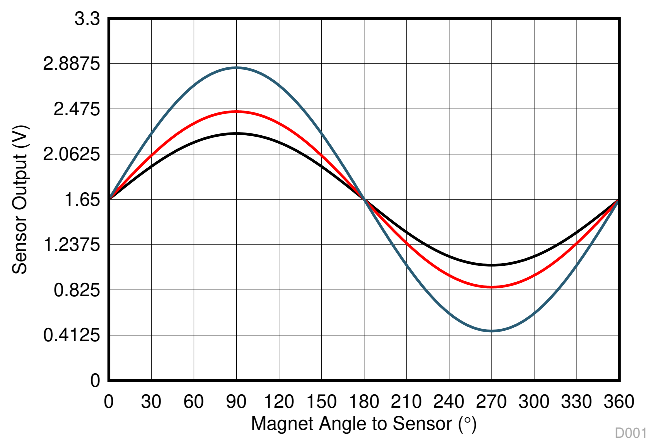

Figure 4-3. One Sensor Uncalibrated Data

4.1.2.2 Calculating Region

To determine the region that the magnet points towards, measure to see if V_{OUT} is greater or less than V_{VCC} / 2, as shown in Table 4-2.

Table 4-2. One Sensor Regions

V_{OUT}	Region
> V_{VCC} / 2	0° to 180°
< V_{VCC} / 2	180° to 360°

4.1.2.3 Accuracy

The accuracy for this setup is the size of each region, 180°.

4.1.3 Two Bipolar Sensors 90° Apart, Uncalibrated

4.1.3.1 Specific Implementation

With two sensors 90° apart, as shown in Figure 4-4, the sensor output voltage takes the form shown in Figure 4-5. There is no calibration phase, so the peak amplitude is unknown; therefore, an example amplitude is shown.

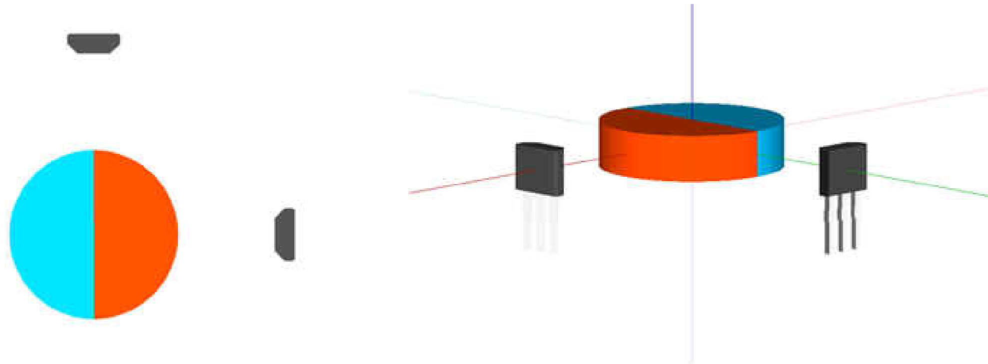

Figure 4-4. Two Sensors 90° Apart

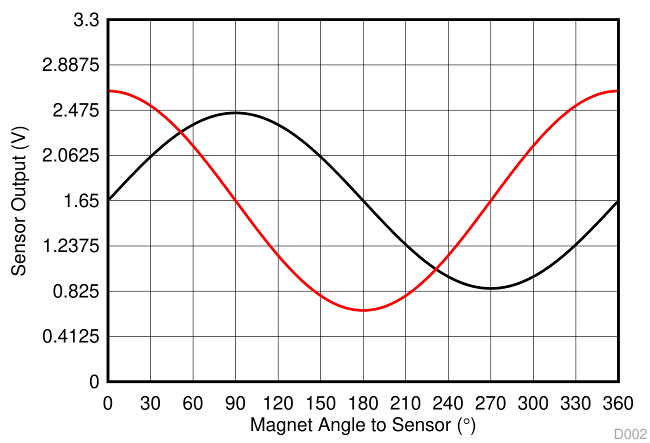

Figure 4-5. Two Sensors 90° Apart Uncalibrated Data

4.1.3.2 Calculating Region

To determine the region that the magnet points towards, measure V_{OUT} for each sensor to see if V_{OUT} is greater or less than V_{VCC} / 2, as shown in Table 4-3.

Table 4-3. Two Sensors 90° Apart Regions

V_{OUT} 1	V_{OUT} 2	Region
> V_{VCC} / 2	> V_{VCC} / 2	0° to 90°
> V_{VCC} / 2	< V_{VCC} / 2	90° to 180°
< V_{VCC} / 2	> V_{VCC} / 2	180° to 270°
< V_{VCC} / 2	< V_{VCC} / 2	270° to 360°

4.1.3.3 Accuracy

The accuracy for this setup is the size of each region, 90°.

4.1.4 Two Bipolar Sensors *n*° Apart, Uncalibrated

4.1.4.1 Specific Implementation

When the two sensors are not 90° apart, the regions sizes are no longer the same, and instead depend on the degree (*n*) between the sensors. With two sensors that are *n*° apart, as in Figure 4-6, the sensor output voltage takes the form shown in Figure 4-7. Both of these images use *n* = 45° as an example. There is no calibration phase, so the peak amplitude is unknown; therefore, an example amplitude is shown. To avoid losing the benefit of two sensors, *n* cannot approximately equal either 0° or 180°.

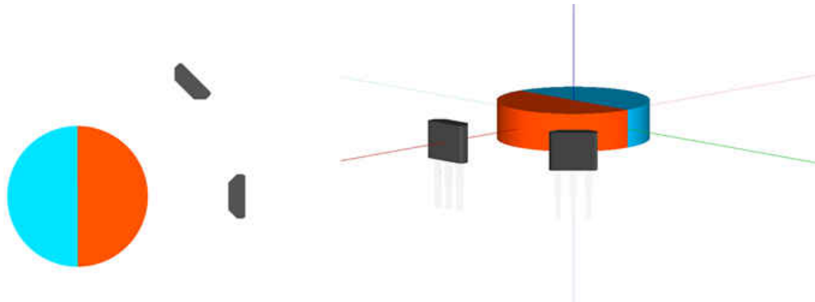

Figure 4-6. Two Sensors 45° Apart

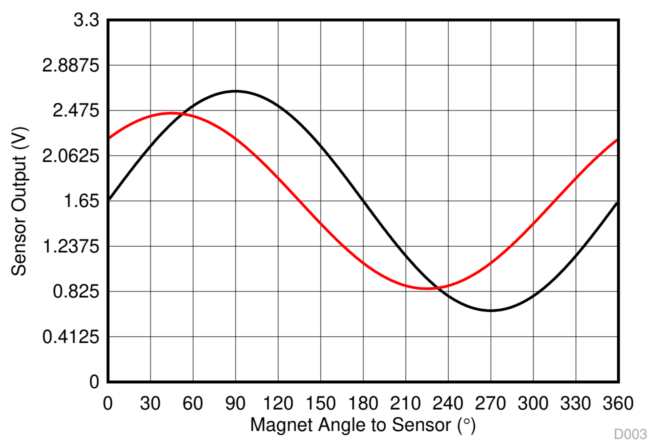

Figure 4-7. Two Sensors 45° Apart Uncalibrated Data

4.1.4.2 Calculating Region

To determine the region that the magnet points towards, measure V_{OUT} for each sensor to see if V_{OUT} is greater or less than V_{VCC} / 2, as shown in Table 4-4.

Table 4-4. Two Sensors 45° Apart Regions

V_{OUT} 1	V_{OUT} 2	Region for *n*	Region at *n* = 45°
> V_{VCC} / 2	> V_{VCC} / 2	0° to (180 – *n*)°	0° to 135°
> V_{VCC} / 2	< V_{VCC} / 2	(180 – *n*)° to 180°	135° to 180°
< V_{VCC} / 2	> V_{VCC} / 2	180° to (360 – *n*)°	180° to 315°
< V_{VCC} / 2	< V_{VCC} / 2	(360 – *n*)° to 360°	315° to 360°

4.1.4.3 Accuracy

The accuracy for this setup depends on the size of the current region. Out of the four regions, two regions have an accuracy of *n*° and the other two regions have an accuracy of (180 – *n*)°.

4.1.5 Three or More Bipolar Sensors, Uncalibrated

4.1.5.1 Specific Implementation

With *s* number of sensors *n*° apart, the sensor system output varies for every setup, but produces *s* × 2 regions. For evenly spaced regions, place the sensors so that n = (180 / *s*)° apart. For example, Figure 4-8 and Figure 4-9 use *s* = 3 sensors and *n* = (180 / 3) = 60° and produces 3 × 2 = 6 regions. Region sizes can be adjusted by changing the degree *n* between each sensor. There is no calibration phase, so the peak amplitude is unknown; therefore, an example amplitude is shown. To avoid losing the benefit of each sensor, *n* between any given two sensors cannot approximately equal either 0° or 180°.

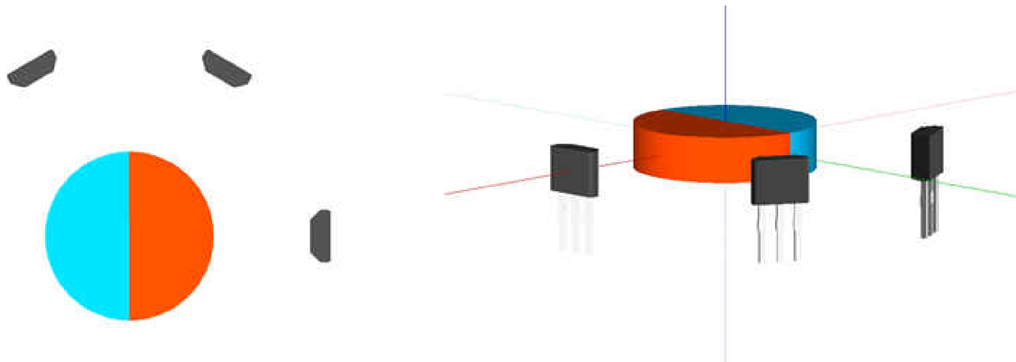

Figure 4-8. Three Sensors 60° Apart

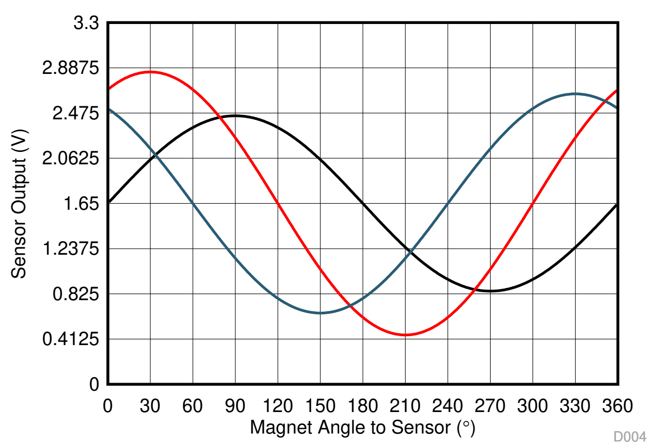

Figure 4-9. Three Sensors 60° Apart Uncalibrated Data

4.1.5.2 Calculating Region

To determine the region that the magnet points towards, measure V_{OUT} for each sensor to see if V_{OUT} is greater or less than V_{VCC} / 2 while considering the degree *n* between each sensor. The regions from the example where *s* = 3 sensors and n = (180 / 3) = 60° are shown in Table 4-5. To calculate the regions when using any other value for *n*, adapt the equations shown in Table 4-4 to adjust for the number of sensors (*s*) and spacing (*n*).

Table 4-5. Three Sensors 60° Apart Regions

V_{OUT} 1	V_{OUT} 2	V_{OUT} 3	Region
> V_{VCC} / 2	> V_{VCC} / 2	> V_{VCC} / 2	0° to 60°
> V_{VCC} / 2	> V_{VCC} / 2	< V_{VCC} / 2	60° to 120°
> V_{VCC} / 2	< V_{VCC} / 2	< V_{VCC} / 2	120° to 180°
< V_{VCC} / 2	< V_{VCC} / 2	< V_{VCC} / 2	180° to 240°
< V_{VCC} / 2	< V_{VCC} / 2	> V_{VCC} / 2	240° to 300°
< V_{VCC} / 2	> V_{VCC} / 2	> V_{VCC} / 2	300° to 360°

4.1.5.3 Accuracy

The accuracy for this setup depends on the current region and the value of *n*. When using evenly spaced regions, where *n* = (180 / *s*)°, the accuracy for each region is (180 / *s*). To determine the accuracy when using any other value for *n*, adapt the method described in Section 4.1.4.3 to adjust for the number of sensors (*s*) and spacing (*n*).

4.2 Peak Calibrated Implementations

4.2.1 Overview

4.2.1.1 General Implementation

With a peak-calibrated system, bipolar sensor data can be normalized to ±1 for use with the arctan2 (two sensors) or arcsin (one sensor) function in order to determine the angle. Arctan2 must be used instead of arctan, because arctan2 accounts for which of the two values are negative. The process for calibration is:

1. Find the min and max values from each sensor by continuously reading voltages while rotating the magnet 360°. One full rotation is required, but more rotations help make sure that more accurate min and max values are found.
2. Then, during normal operation, each new measured voltage can be normalized to ±1 using Equation 1.

$$NORM = \frac{V_{measured} - V_{min} - V_{amplitude}}{V_{amplitude}} \quad where \quad V_{amplitude} = \frac{V_{max} - V_{min}}{2} \tag{1}$$

3. The normalized data is then put directly into the arctan2 (two sensors, 0° to 360° output) or arcsin (one sensor, 0° to ±90° output) function in order to get the angle of the magnet.

4.2.1.2 Preferred Magnet Types

- Diametrically magnetized disc or cylinder

4.2.1.3 General Accuracy and Resolution

- Good accuracy, ≈ 8° max error peak-to-peak (found experimentally using the DRV5055)
- High resolution is possible (depending on ADC)
- Results come in degrees
- Accuracy is affected by physical setup and magnet selection

4.2.1.4 Considerations

- The magnet must be oriented to align the degree output to the desired physical location.
- The sensors and magnet must be placed so that the sensor voltage output is not clipped or railed at either the north or south pole.
- If writing code that uses both the arctan2 and arcsin functions, consider using the identity in Equation 2. This identity saves on program space because the arctan2 function already uses the arctan function.

$$arcsin\left(x\right) = 2 \times arctan\left(\frac{x}{1 + \sqrt{1 - x^2}}\right) \tag{2}$$

- Most arctan2 and arcsin functions output the angle in radians. The angle can be converted to degrees using Equation 3.

$$A° = A_r \times \frac{180}{\pi} \tag{3}$$

- While a ±90° range is possible with one sensor, the voltage measurement accuracy and sensor noise limit the angle to a value less than ±90°.

4.2.2 One Bipolar Sensor, Peak Calibrated

4.2.2.1 Specific Implementation

With one sensor, as in Figure 4-2, the sensor output voltage takes the form shown in Figure 4-10. With a peak calibration phase, both the min and max voltage values are known.

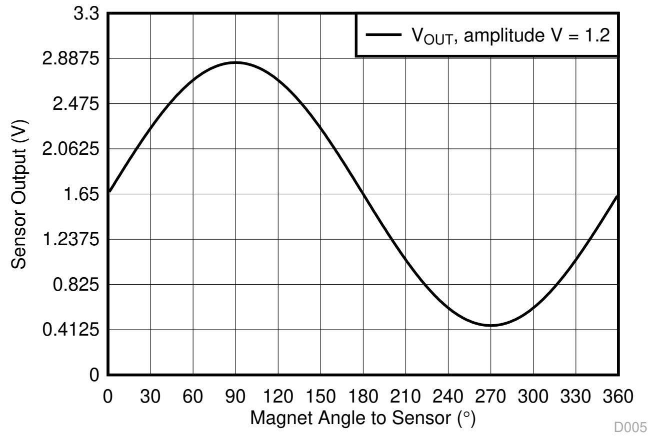

Figure 4-10. One Sensor Peak Calibrated Data

4.2.2.2 Calculating Angle

To determine the angle that the magnet points towards, input the normalized data into the arcsin function, as outlined in Section 4.2.1.1. The identity in Equation 2 may be used instead of arcsin if desired.

4.2.2.3 Accuracy

The output from the arcsin function has a swing of ±90°. However, the accuracy generally decreases when the angle is too close to 90° or –90° because there is not much variance in the output voltage for those regions. In general, the accuracy is usually within 8° peak-to-peak when operating at a swing of ≈±80°, based on datasheet parameters and experimental data taken with the DRV5055. Figure 4-11 shows an example of a possible error curve for this setup.

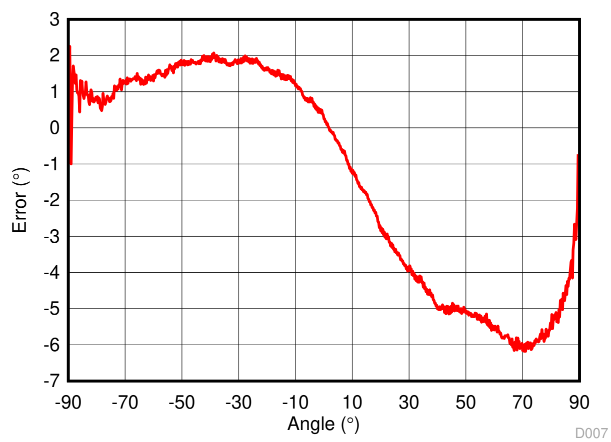

Figure 4-11. One Sensor Peak Calibrated Error

4.2.3 Two Bipolar Sensors 90° Apart, Peak Calibrated

4.2.3.1 Specific Implementation

With two sensors 90° apart, as in Figure 4-4, the sensor output voltage takes the form shown in Figure 4-12. With a peak calibration phase, both the min and max voltage values are known for each curve.

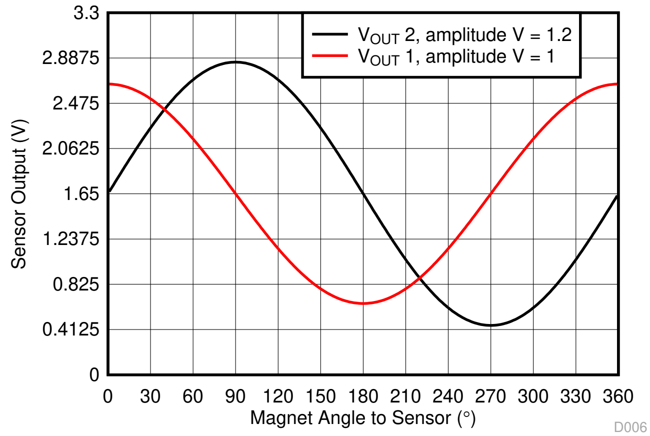

Figure 4-12. Two Sensors Peak Calibrated Data

4.2.3.2 Calculating Angle

To determine the angle that the magnet points towards, input the normalized data into the arctan2 function, as outlined in Section 4.2.1.1.

4.2.3.3 Accuracy

The output from the arctan2 function goes from 0° to 360°. In general, the accuracy is usually within 8° peak-to-peak, based on datasheet parameters and experimental data taken with the DRV5055. Figure 4-13 shows an example of a possible error curve for this setup.

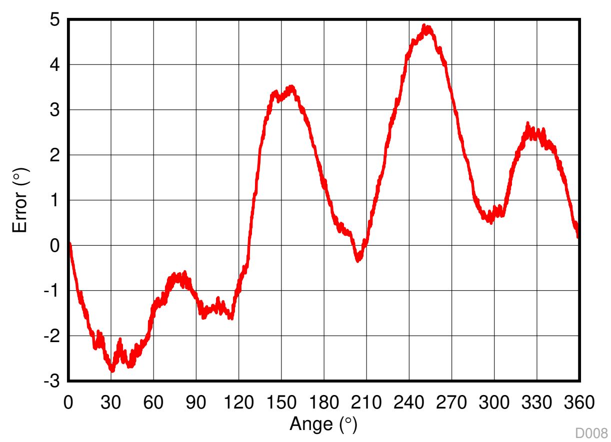

Figure 4-13. Two Sensors Peak Calibrated Error

4.3 Lookup Table Calibration Implementations

4.3.1 Overview

4.3.1.1 General Implementation

With a lookup table calibrated system, sensor voltage data for known angles are recorded, and then the angle for any measured voltage is taken from a linear interpolation between the known voltages. The process for calibration is:

1. For each desired calibration angle, rotate the magnet to the angle, and record the measured voltage for each sensor.
2. Then, during normal operation, measured voltages for each sensor fall between two of the previously recorded voltages, referenced as V_{above} and V_{below}. When using two sensors, make sure that the V_{above} and V_{below} for each sensor are associated with the same calibration angle.
3. The measured angle is then taken as a ratio of those two voltages and the respective known angles using Equation 4:

$$ANGLE_{new} = \frac{V_{measured} - V_{below}}{V_{above} - V_{below}} \times \left(ANGLE_{above} - ANGLE_{below}\right) + ANGLE_{below} \quad (4)$$

Note

It is important to note that calibration regions where $V_{above} - V_{below} \approx 0$ do not work in Equation 4, and therefore must not be used for this method.

4.3.1.2 Preferred Magnet Types

- Diametrically magnetized disc or cylinder

4.3.1.3 General Accuracy and Resolution

- High accuracy is achievable, but depends significantly on the number of calibration points used. A good starting point to estimate the spacing (in degrees) needed between calibration points for a desired peak-to-peak accuracy (in degrees) is found using Equation 5, based on experimental data collected with the DRV5055. This equation uses peak-to-peak error, so a peak-to-peak accuracy of 1° gives an approximate error of ±0.5°. With a lookup table calibration, the spacing between calibration points must not be greater than 30°, or the error may be unpredictable.

$$Spacing \approx Accuracy * 8 \quad (5)$$

- High resolution is possible (depending on ADC)
- Results come in degrees
- Accuracy is also affected by physical setup (when using one sensor) and magnet selection

4.3.1.4 Considerations

- The magnet does not need to be oriented when using two sensors, and only needs to be roughly oriented when using one sensor because a 0° point can be set during calibration.
- The sensors and magnet must be placed so that the sensor voltage output is not clipped or railed at either the north or south pole.
- 0° and 360° are the same angle; therefore, use 0 as $ANGLE_{below}$ and 360 as $ANGLE_{above}$ in Equation 4.
- Although it is possible to measure voltages that are out of the range of the lookup table (either above the max or below the min recorded voltage values), the absolute min and max values are unknown. Therefore, these measurements are unusable for linear interpolation.
- The lookup table calibration method can be more difficult to implement when using two sensors than methods that use the arctan2 function for the following reasons:
  – Exceptions must be coded to account for when $V_{above} – V_{below} \approx 0$ V in order to avoid dividing by 0.
  – Data from the nonlinear regions of each sensor output must be avoided.
  – Calibration data for each sensor must be stored (instead of storing the arctan2 output); therefore:
    - It is harder to determine which calibration region to use because the voltage from each sensor appears in two different regions of the respective lookup tables.
    - It is possible that near a calibration boundary line, the data from each sensor is on either side of that boundary.

4.3.2 One Bipolar Sensor, Lookup Table Calibrated

4.3.2.1 Specific Implementation

With one sensor, as in Figure 4-2, the sensor output voltage takes the form shown in Figure 4-10. With a lookup table calibration phase, specific voltages for various angles are known, but the min and max voltage values are not known.

4.3.2.2 Calculating Angle

To determine the angle that the magnet points towards, find the estimated angle between two lookup table points, as outlined in Section 4.3.1.1.

4.3.2.3 Accuracy

With just one sensor, only the linear region of the curve in Figure 4-10 is usable. This span is ≈140°; therefore, the magnet must be roughly positioned so that the desired measurement range falls within the 140° linear region. The accuracy for this method largely depends on the spacing between the calibration points, and is estimated using Equation 5.

Figure 4-14, Figure 4-15, and Figure 4-16 each show an example of a possible error curve for this setup with a different number of calibration points, calibrated between ±70°.

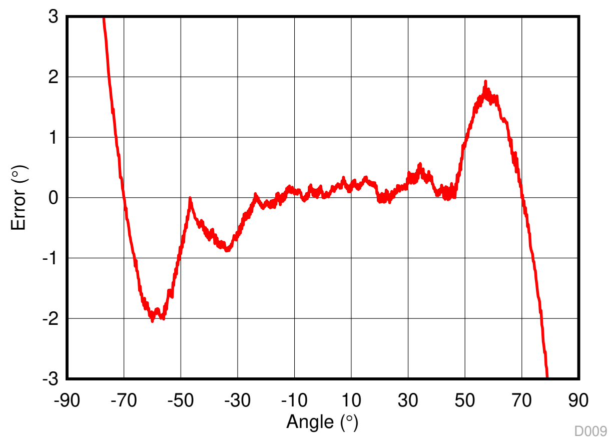

Figure 4-14. One Sensor Lookup Table Calibrated Error, 7 Cal Points, ≈ 4° Peak-to-Peak Error

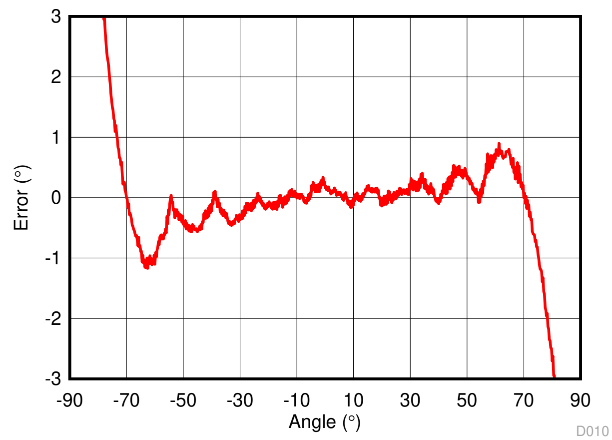

Figure 4-15. One Sensor Lookup Table Calibrated Error, 10 Cal Points, ≈ 2° Peak-to-Peak Error

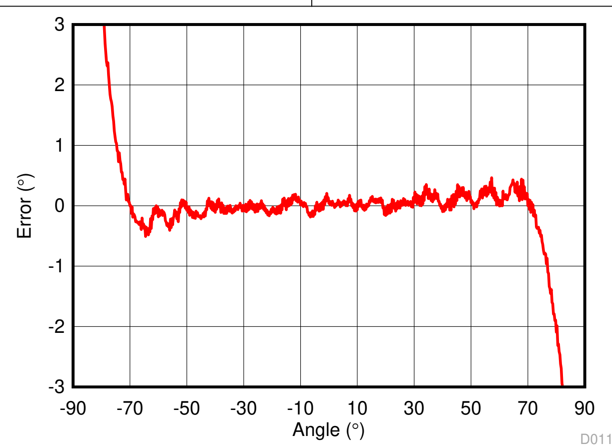

Figure 4-16. One Sensor Lookup Table Calibrated Error, 16 Cal Points, ≈ 1° Peak-to-Peak Error

4.3.3 Two Bipolar Sensors ≈ 90° Apart, Lookup Table Calibrated

4.3.3.1 Specific Implementation

With two sensors, as in Figure 4-4, the sensor output voltage takes the form shown in Figure 4-12. These sensors do not need to be 90° apart to have unique data for the lookup table. However, best practice is to have the sensors close to 90° apart so that the unusable peaks of one signal are at the linear regions of the other signal, allowing the peak data to be ignored. To avoid losing the benefit of two sensors, the spacing cannot be approximately equal to either 0° or 180°. With a lookup table calibration phase, specific voltages for various angles are known, but the min and max voltage values are not known.

4.3.3.2 Calculating Angle

To determine the angle that the magnet points towards, find the estimated angle between two lookup table points, as outlined in Section 4.3.1.1. This process must be done for each sensor, and then the two results are averaged to find the angle associated with the magnet. Areas where $V_{above} - V_{below} \approx 0$ (the peaks) are not usable in this method; therefore, the best practice is to use the value from the other sensor in these regions.

4.3.3.3 Accuracy

The accuracy for this method largely depends on the spacing between the calibration points, and can be estimated using Equation 5.

Figure 4-17, Figure 4-18, and Figure 4-19 each show an example of a possible error curve for this setup with a different number of calibration points.

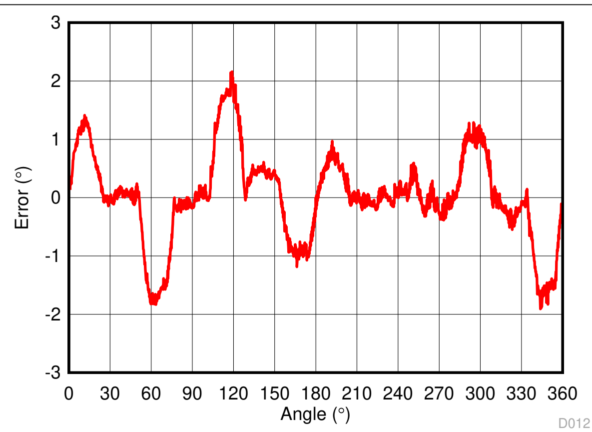

Figure 4-17. Two Sensors Lookup Table Calibrated Error, 14 Cal Points, ≈ 4° Peak-to-Peak Error

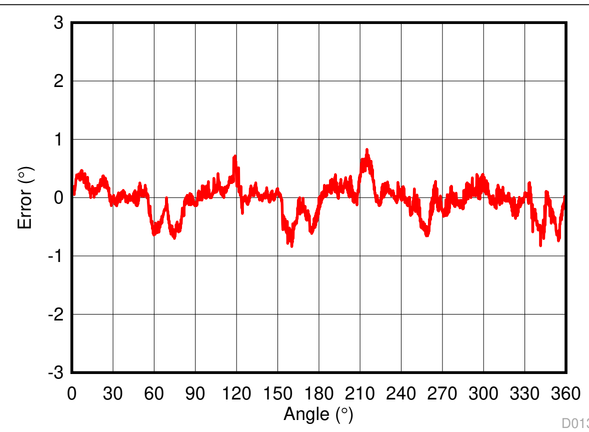

Figure 4-18. Two Sensors Lookup Table Calibrated Error, 26 Cal Points, ≈ 2° Peak-to-Peak Error

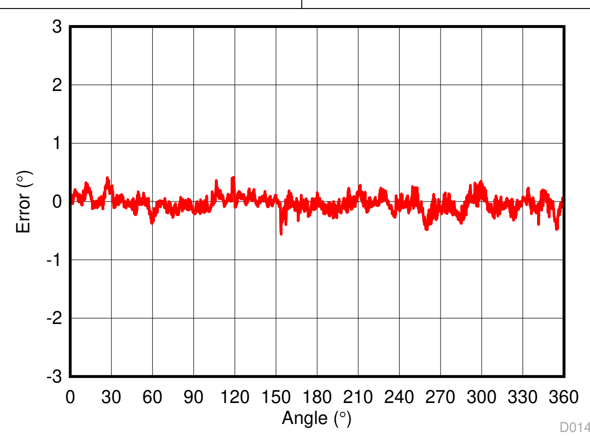

Figure 4-19. Two Sensors Lookup Table Calibrated Error, 45 Cal Points, ≈ 1° Peak-to-Peak Error

4.4 Peak Calibrated Plus Lookup Table Hybrid

4.4.1 Overview

4.4.1.1 General Implementation

With a peak calibrated plus lookup table hybrid system, bipolar sensor data is first normalized to ±1 for use with the arctan2 (two sensors) or arcsin (one sensor) function to determine a preliminary angle (A_p). Arctan2 must be used instead of arctan because arctan2 accounts for which of the two values are negative. Then the calculated A_p for various known ideal angles (A_i) are recorded as calibration angles (A_c), and a linear error adjustment is done to all future A_p based on the error between the recorded A_c and the known A_i. The process for calibration is:

1. Find A_p by inputting the normalized data into the arctan2 or arcsin function, as outlined in Section 4.2.1.1).
2. Rotate the magnet to the 0° point and use this A_p as a zero-offset for all other A_p calculations.
3. Rotate the magnet to the desired calibration A_i and record the A_p as A_c. (The A_c for 0° is 0° because of the zero-offset adjustment done previously).
4. Then, during normal operation, each new A_p falls between two of the previously recorded A_c; the angle just above A_p (A_{cA}) and the angle just below A_p (A_{cB}).
5. The error for any point between A_{cA} and A_{cB} is estimated from a linear approximation of the known error from A_{cA} to A_{iA} and A_{cb} to A_{iB} in the form of y = Mx + b, where:

$$M = \frac{A_{iA} - A_{iB}}{A_{cA} - A_{cB}}, \quad and \quad B = A_{iA} - \left(A_{cA} \times M\right) \tag{6}$$

6. Then, all new angle values (A_n) can be calculated using Equation 7:

$$A_n = \left(M \times A_p\right) + B \tag{7}$$

4.4.1.2 Preferred Magnet Types

- Diametrically magnetized disc or cylinder

4.4.1.3 General Accuracy and Resolution

- High accuracy is achievable, but significantly depends on the number of calibration points used. A good starting point to estimate the spacing (in degrees) needed between calibration points for a desired peak-to-peak accuracy (in degrees) is found using Equation 8, based on experimental data collected with the DRV5055. This equation uses peak-to-peak error, so a peak-to-peak accuracy of 1° gives an approximate error of ±0.5°.

$$Spacing \approx Accuracy \times 15 \tag{8}$$

- High resolution is possible (depending on ADC).
- Results come in degrees.
- Accuracy is also affected by physical setup and magnet selection.

4.4.1.4 Considerations

- When using two sensors, the magnet does not need to be oriented. When using one sensor, the magnet only needs to be roughly oriented because a 0° point can be set during calibration.
- The sensors and magnet must be placed so that the sensor voltage output is not clipped or railed at either the north or south pole.
- 0° and 360° are the same angle; therefore, use 0 as A_{iB} and use 360 as A_{iA} in Equation 6.
- If writing code that uses both the arctan2 and arcsin functions, consider using the identity in Equation 9, which saves on program space because the arctan2 function already uses arctan.

$$arcsin\left(x\right) = 2 \times arctan\left(\frac{x}{1 + \sqrt{1 - x^2}}\right) \quad (9)$$

- Most arctan2 and arcsin functions output the angle in radians. This angle can be converted to degrees using Equation 10:
  – $$A° = A_r \times \frac{180}{\pi} \quad (10)$$
- While a ±90° range is possible with one sensor, the voltage measurement accuracy and sensor noise limit the angle to a value less than ±90°.

4.4.2 One Bipolar Sensor, Hybrid Calibrated

4.4.2.1 Specific implementation

With one sensor, as shown in Figure 4-2, the sensor output voltage takes the form shown in Figure 4-10. With a lookup table plus peak calibration phase, specific voltages for various angles, as well as the min and max voltage values, are known.

4.4.2.2 Calculating Angle

To determine the angle that the magnet points towards, input the normalized data into the arcsin functionand calibrating for accuracy using a lookup table, as outlined in Section 4.4.1.1. The identity in Equation 9 may be used instead of arcsin, if desired.

4.4.2.3 Accuracy

The output from the arcsin function has a swing of ±90°, but the accuracy generally decreases when too close 90° or -90°, as there is not much variance in the output voltage for those regions. In general, this leaves an operating region of ≈±80°. Therefore, the magnet needs to be roughly positioned so that the desired measurement range falls within the ±80° region. The accuracy for this method largely depends on the spacing between the calibration points, which can be estimated using Equation 8.

Figure 4-20, Figure 4-21, and Figure 4-22 each show an example of a possible error curve for this setup with a different number of calibration points, calibrated between ±80°.

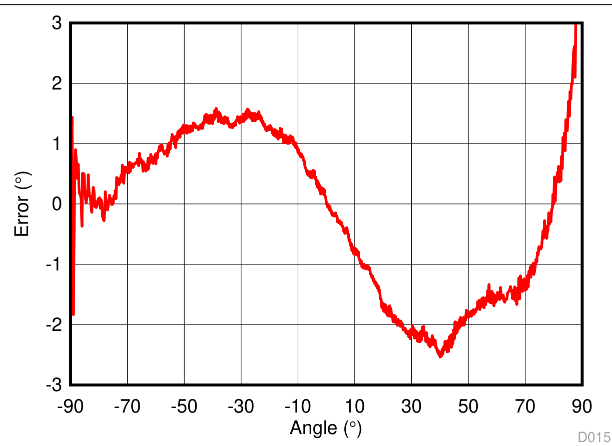

Figure 4-20. One Sensor Peak Calibrated Plus Lookup Table Error, 3 Cal Point, ≈ 4° Peak-to-Peak Error

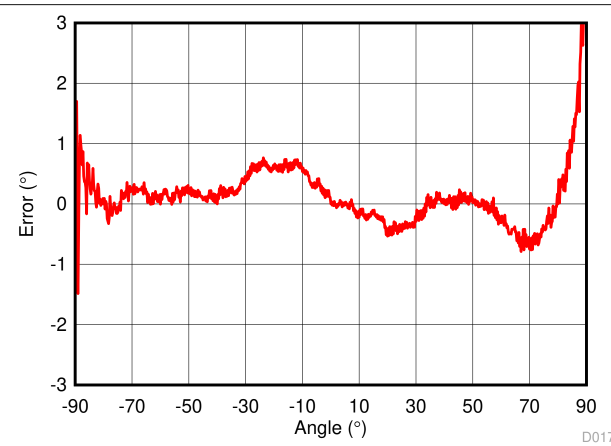

Figure 4-21. One Sensor Peak Calibrated Plus Lookup Table Error, 5 Cal Points, ≈ 2° Peak-to-Peak Error

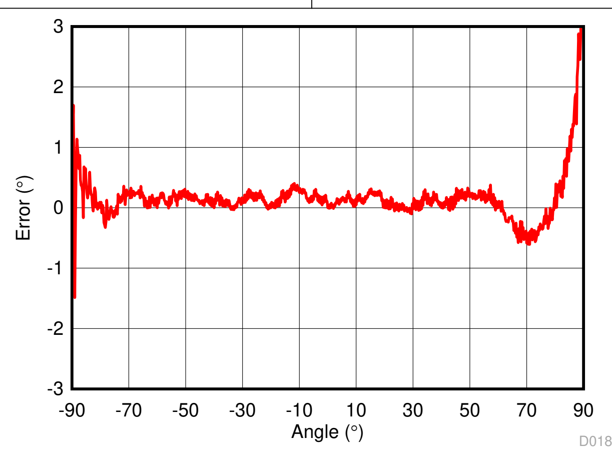

Figure 4-22. One Sensor Peak Calibrated Plus Lookup Table Error, 9 Cal Points, ≈ 1° Peak-to-Peak Error

4.4.3 Two Bipolar Sensors 90° Apart, Hybrid Calibrated (Recommended High Accuracy Method)

Note

This is the method that is used on the DRV5055-ANGLE-EVM.

4.4.3.1 Specific Implementation

With two sensors at 90° apart as in Figure 4-4, the sensor output voltage will take the form shown in Figure 4-12. Note that with a lookup table plus peak calibration phase, specific voltages for various angles are known, as well as the min and max voltage values.

4.4.3.2 Calculating Angle

To determine the angle that the magnet points towards, input the normalized data into the arctan2 function and calibrating for accuracy using a lookup table, as outlined in Section 4.4.1.1.

4.4.3.3 Accuracy

The accuracy for this method largely depends on the spacing between the calibration points, and can be estimated using Equation 8.

Figure 4-23, Figure 4-24, and Figure 4-25 each show an example of a possible error curve for this setup with a different number of calibration points.

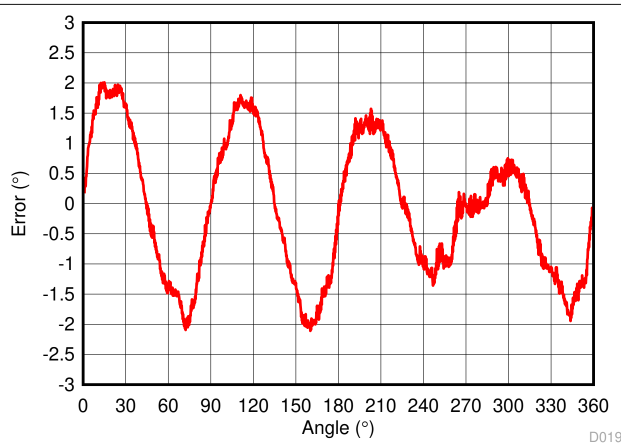

Figure 4-23. Two Sensors Peak Calibrated Plus Lookup Table Error, 8 Cal Points, ≈ 4° Peak-to-Peak Error

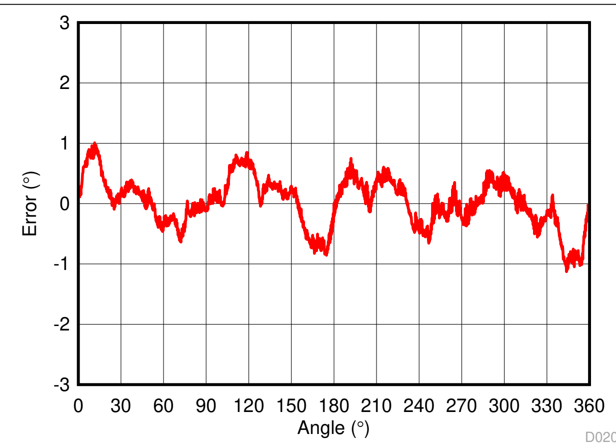

Figure 4-24. Two Sensors Peak Calibrated Plus Lookup Table Error, 14 Cal Points, ≈ 2° Peak-to-Peak Error

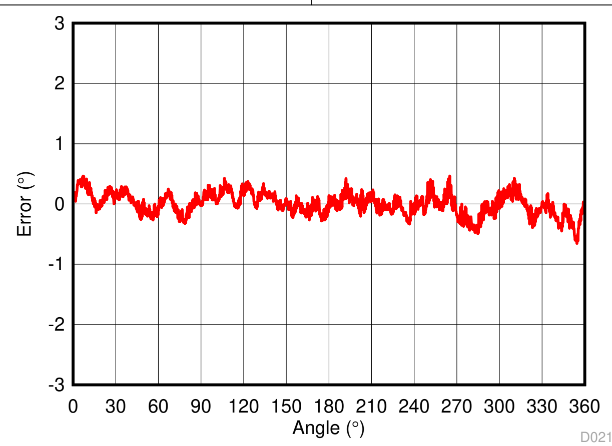

Figure 4-25. Two Sensors Peak Calibrated Plus Lookup Table Error, 25 Cal Points, ≈ 1° Peak-to-Peak Error

5 References

- Texas Instruments, *Overview Using Linear Hall Effect Sensors to Measure Angle* application brief
- Texas Instruments, Breakout Adapter for SOT-23 and TO-92 Hall Sensor Evaluation Module tools page
- Texas Instruments, DRV5055 Evaluation Module tools page
- Texas Instruments, *DRV5055-ANGLE-EVM* tools page
- Texas Instruments, *Angle Measurement With Multi-Axis Linear Hall-Effect Sensors* application report
- Texas Instruments, E2E forums at https://e2e.ti.com/

6 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision A (August 2018) to Revision B (November 2021) **Page**

- Updated the numbering format for tables, figures, and cross-references throughout the document.................. 1
- Updated the *Abstract*.......... 1
- Updated the *References*.......... 23

Changes from Revision * (July 2018) to Revision A (August 2018) **Page**

- Changed document title.......... 1