Dynamic Motor Motion
Technology Corporation

DMM Technology Corp.

ABS-16-00-GP1 Absolute Encoder

Accuracy Study

March 02, 2017
Version 1.0

Introduction

For high precision motion control, the accuracy, resolution and repeatability of the encoder is critical to overall dynamic performance. The accuracy of an encoder is defined as the difference between the real angle and the encoder's measured output angle.

Traditionally, accuracy of magnetic encoders are not as high as optical encoders. This is due to magnetic encoder factors such as:

- Non-linearity of hall sensor magnetic sensitivity
- Non-symmetrical flux field of magnetic hub
- Misalignment (eccentricity) of magnetic hub and sensor
- Environmental electrical/magnetic noise

Unlike traditional magnetic encoders that place a single sensor above the magnetic hub, the DMM ABS-16-00-GP1 encoder uses a single pole pair NeFdB magnet mounted around the servo motor shaft. There are 8 linear hall sensors mounted circularly around the magnet, then each 8 analog readings are calculated into 1 absolute position reading.

Measured against a traditional 2500line optical encoder, the ABS-16 encoder has relatively lower accuracy measurements. But there are many fundamental measurement errors associated with the 2500line encoder and all other optical encoders.

The ABS-16 encoder, and all other magnetic encoders also have associated measurement errors. But the ABS-16 magnetic encoder has a real-time algorithm to ensure measured position and accuracy is independent of mounting or environmental measurement errors. We will compare and study the encoder accuracy of magnetic and optical encoders from measured data and theory.

Measurement Apparatus

The data for our measurement is taken from a calibration device as shown in Figure 1 and Figure 2. A DMM 0.4kW servo motor (left) is coupled directly to a servo motor mounted with a conventional 2500line optical encoder (right). The data from both encoders is read by a proprietary device with a refresh rate of 300ms.

Figure 1. Overall Measurement System

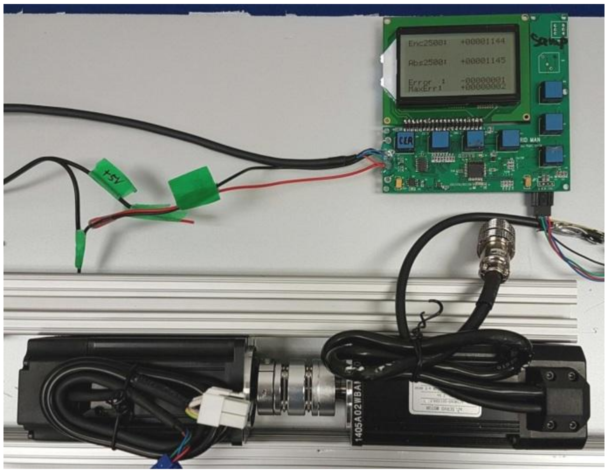
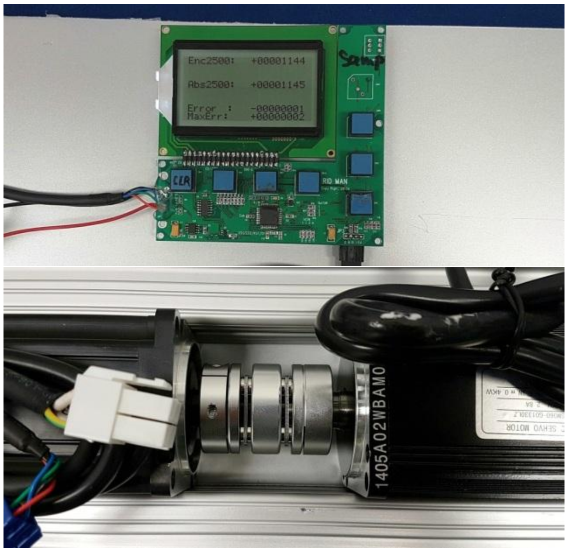


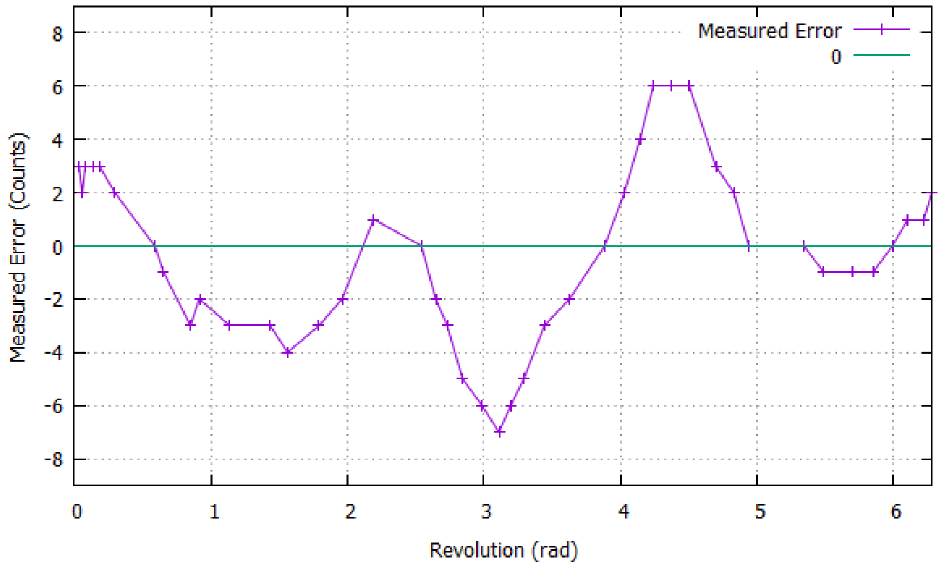
Figure 2. Measurement device and motor coupling



Accuracy Measurement and Analysis

In order to test the accuracy of the DMM ABS-16 encoder, we couple a traditional 2500line optical incremental encoder to the ABS-16 encoder and measure/compare both position readings. The encoders are both mounted onto 0.4kW servo motors. The output resolution of the ABS-16 encoder is scaled from 65,536counts to 10,000counts.

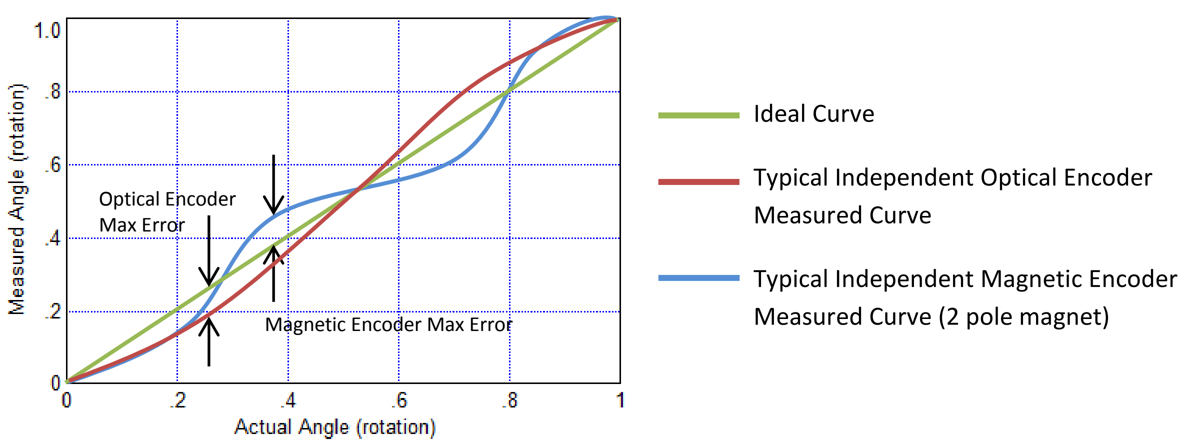
Figure 3. Measured error of ABS-16 encoder against 2500line encoder



The measured error is calculated as (2500line encoder reading) – (ABS-16 encoder reading). From the figure above, the maximum measured error between the two encoders is 7 counts.

This measurement assumes that the 2500line optical encoder's position is perfect. However in reality, there are many factors that contribute to the measurement error of optical encoders. From theory, we know the measurement error of (2 pole) magnetic and optical encoders looks like the following:

Figure 4. Ideal measured position versus typical optical and magnetic measured positions



Since the data in Figure 3. compares the ABS-16 absolute encoder's readings to the 2500line optical encoder's readings, the measurement errors in the 2500line encoder causes a greater magnitude of error in the ABS-16 encoder's readings. So in order to estimate the ABS-16 encoder's independent measurement error, we take into consideration that:

(ABS-16 independent error) = (ABS-16 combined/measured error) – (2500line encoder independent error)

In the above equation, "ABS-16 combined error" is the maximum error in Figure 3. We know that measured against the Ideal Curve, the magnetic encoder's error is the independent error. But measured against the optical encoder, which is the data in Figure 3., the maximum error is the combined independent error of both ABS-16 magnetic encoder and 2500line optical encoder. Since the 2500line encoder independent error is unknown, we can estimate this number from their typical curves.

Figure 5. ABS-16 encoder typical measurement and measured against 2500line optical encoder

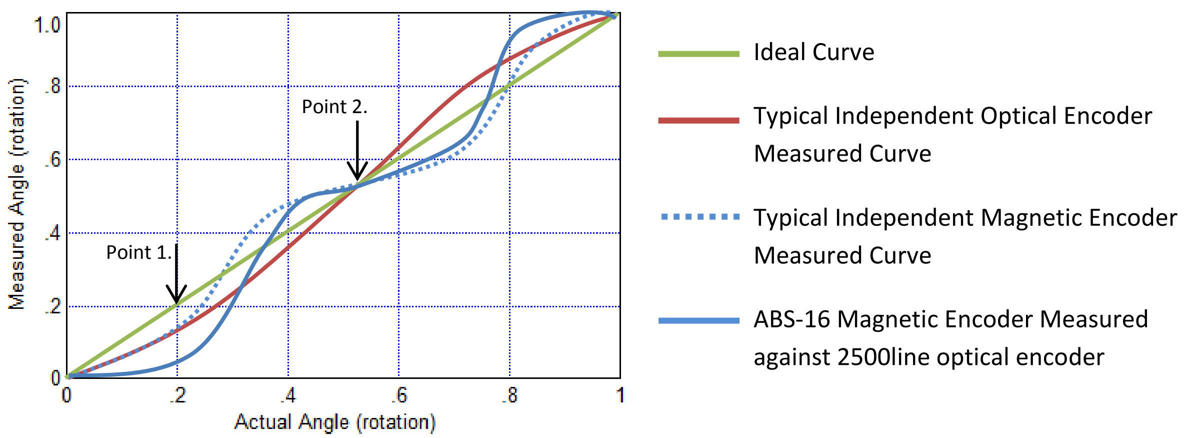
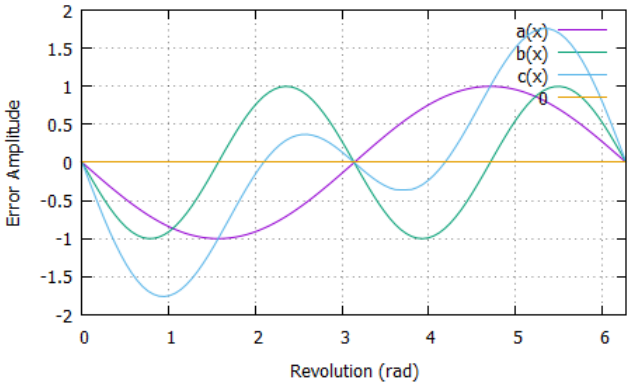


Figure 5. shows the difference between the ABS-16 encoder's independent errors versus ABS-16 encoder's measured error against 2500line encoder. At Point 1, both the 2500line encoder and ABS-16 encoder's independent error is maximum, so the ABS-16 encoder's measured error is highest. But at Point 2, both the 2500line and ABS-16 encoder's independent error is zero, so the ABS-16 encoder's measured error is zero.

Depending on the phasing between the individual errors, the total measured error, or combined error is different. Figure 6 shows two examples of possible phasing. The magnetic encoder independent error b(x) and optical encoder independent error a(x) are plotted against a linear axis for clarity and are represented by sin(2x-α) and sin(x- α) respectively. The combined error c(x) is represented by a(x)+b(x).

Figure 6. Error phasing and combined error

Example 1.



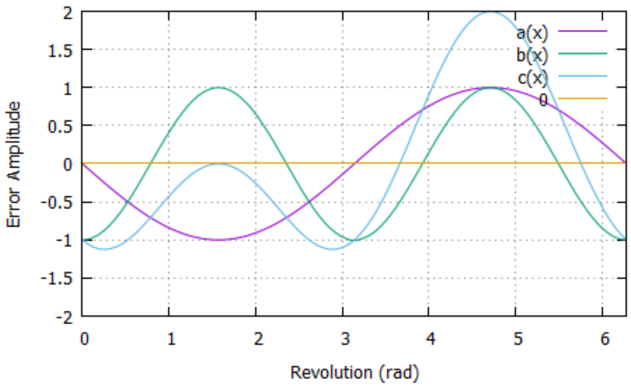
a(x) = Optical encoder independent error

b(x) = Magnetic encoder independent error

c(x) = a(x) + b(x)
= Combined error
= Measured error in Figure.3

The phasing in Example 1 leads to 2 large peaks and 2 small peaks in combined error. Similar to data in Figure 3.

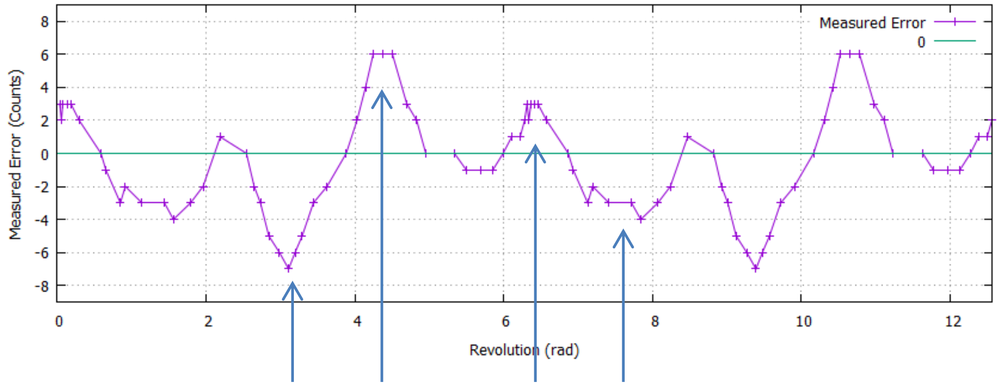
Example 2.



The phasing in Example 2 leads to 1 large peak and 3 small peaks in combined error.

In Figure 6, we see that depending on the phasing of the magnetic encoder and optical encoder's error, the combined error can have different effects. The combined error is the same as the measured error in Figure 3. If the data in Figure 3 is compared to the two examples in Figure 6, we can see a close relationship between the data and Example 1. If the data in Figure 3 is repeated and expanded to 2 revolutions, it clearly shows two large peaks and two small peaks.

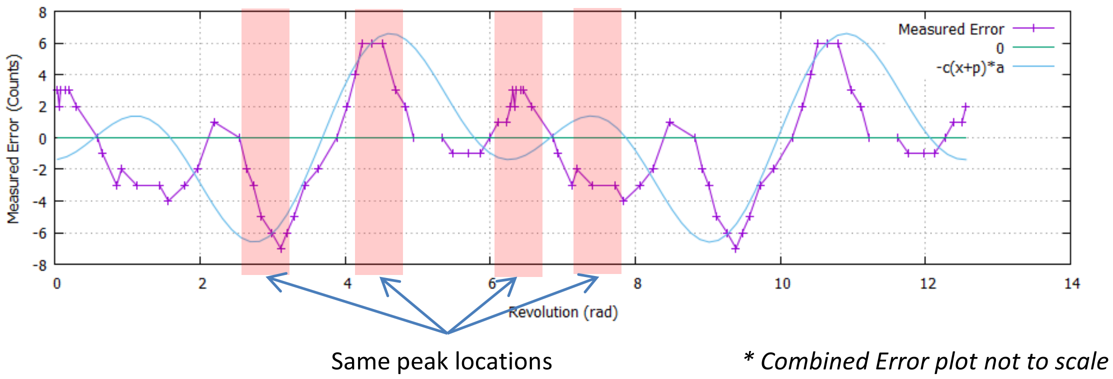
Figure 7. Data from figure 3 expanded to 2 revolutions



2 Large peaks 2 Small peaks

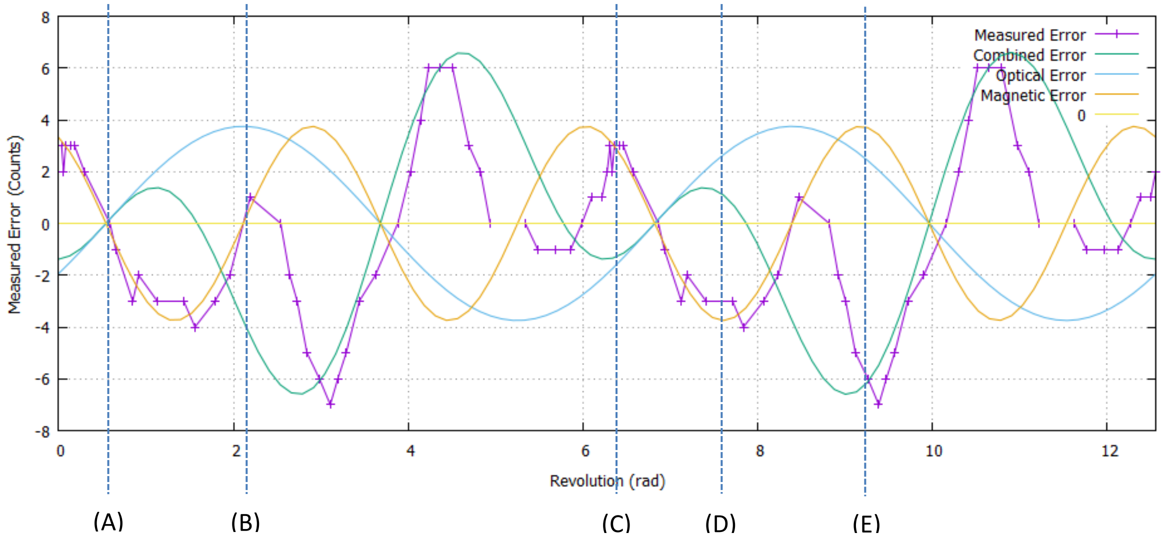
If we overlay the theoretical combined error c(x) to this data, we can see the relationship between the theoretical and measured data from the location of the peaks. The exact location of the peaks is slightly different and this is most likely caused by intrinsic differences between theoretical models and actual device measurements. The theory assumes all errors are ideal and symmetric, but the actual encoder device is affected by many conditions that change its error reading and location about the circle.

Figure 8. Relationship of theoretical error and measured error



The combined error is a combination of magnetic encoder independent error b(x) and optical encoder independent error a(x). By including a(x) and b(x), we can approximate each independent error.

Figure 9. Total error approximation **All data except Measured Error not to scale*

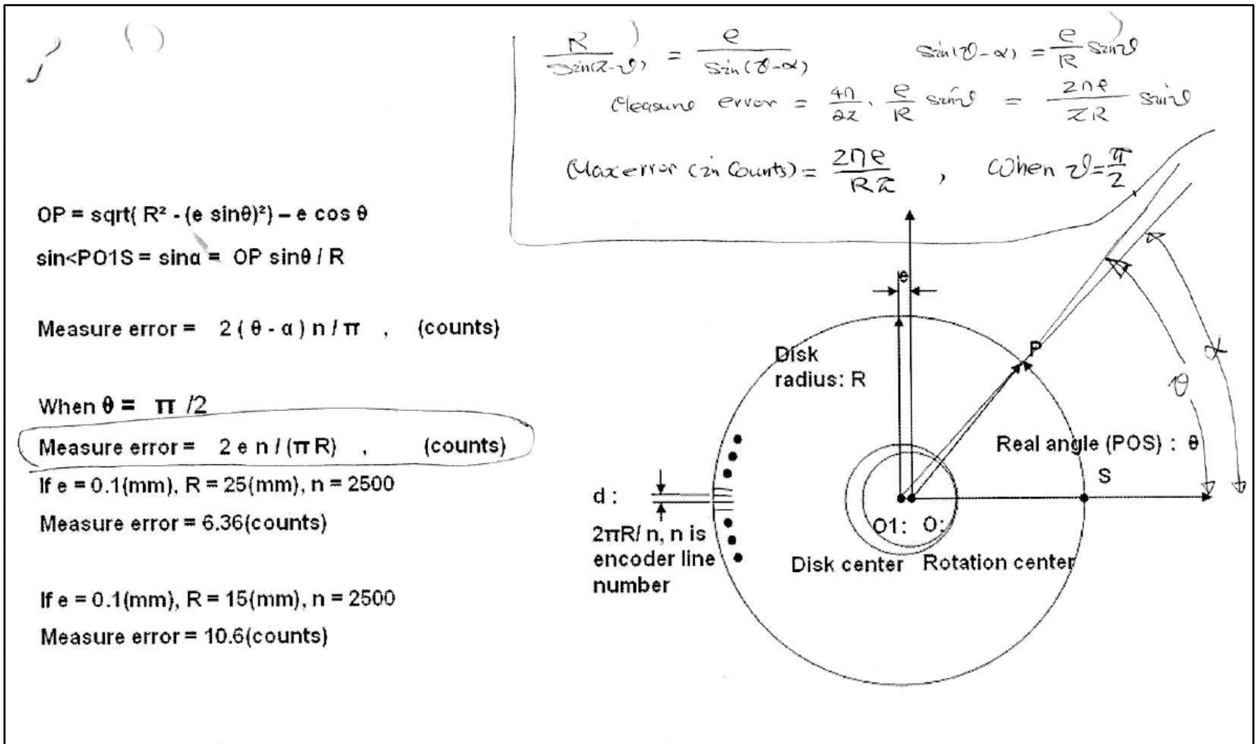


Point A in Figure 9 represents the nodes at which all error is zero. The measured error at all nodes are zero, which means our phasing approximation is accurate. The plots for the combiner error, magnetic encoder error and optical encoder error are all not to scale, so we can approximate only at certain critical points.

At point B, the magnetic encoder's error is zero, but the optical encoder's error is maximum. The measured error at point B is 1 count so we can conclude that the 2500line optical encoder's independent error is +/-1 count (out of 10,000counts). At point C, the measured error is mostly magnetic encoder error. The measured error is 3 counts so assuming all of this is magnetic encoder error, the ABS-16 magnetic encoder's independent error is +/-3 count. At point D, the measured error is 3 counts. At this point ,the optical encoder's error is approximately half, and the magnetic encoder's error is maximum. Since the optical encoder's independent error is 1 count, the ABS-16 magnetic encoder's independent error is 2.5 counts. At point E, the measured error is 7 counts. Since the optical and magnetic encoder's individual error has a combined maximum of 4 counts, there is an additional 3 counts of measured error coming from external sources, which may be caused by coupling, servo motor mechanicals or measurement effects.

Optical Encoder Measurement

In 2005, during development of DMM's previous 14-bit absolute encoder (Model# ABS-14-00), the 14-bit encoder was tested alongside many 2500line optical encoders to verify accuracy. During this development, it was proven that the dimensional mounting tolerance of the 2500line optical encoder contributes to large errors in measurement accuracy. For example, the eccentricity of the optical disk center and actual rotation center can cause large measurement errors:



For the encoder measurement

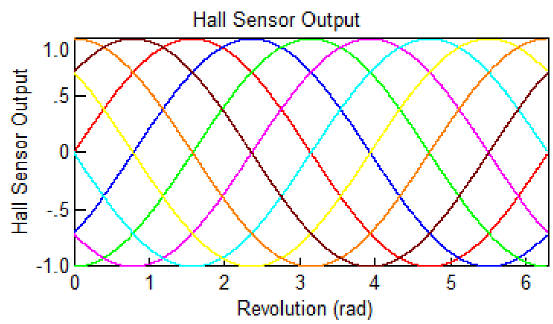
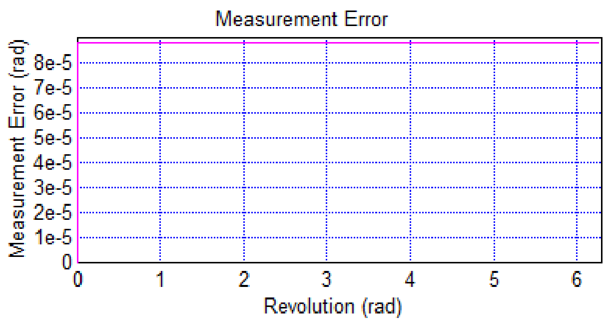
In this calculation, if the eccentricity is dimensionally not centered by 0.1mm, then the measurement error will be 10.6 counts (10/10000*360=0.38˚). If the eccentricity error is 0.01mm, the measurement error will be 1.06 counts (0.038˚). For example, common ball bearings used on optical encoder shafts have a 0.01mm tolerance. Bearings that hold the motor shaft can have even higher tolerances that can cause misalignment between the optical disk and actual rotation center.

Other manufacturers have also recognized the measurement errors of optical encoders. Renishaw plc states that combined effects of system error and installation error can cause reading errors of a few arc-seconds (Ref. 1). Zettlex UK Ltd. states that a 0.025mm mounting eccentricity error can cause up to 412 arc-seconds of measurement error on a 25mm diameter optical disk (Ref. 2).

ABS-16 Encoder Measurement Reliability

During calculation of the position, the ABS-16 encoder uses a unique algorithm that filters out environmental and mounting errors. This means no matter now the magnetic hub or encoder sensor is mounted, the ABS-16 encoder always maintains ideal reading conditions and low measurement error.

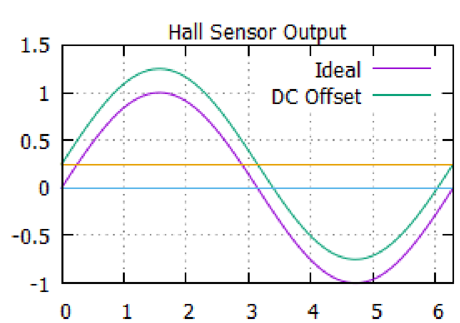
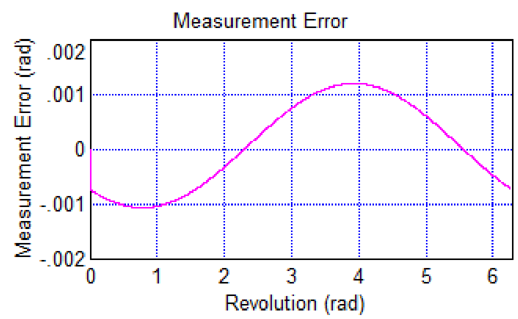
We can test the ABS-16 encoder's algorithm by simulating errors and non-linearities in the hall sensor measurements. Figure 10. shows the ideal reading of the ABS-16 encoder, which assumes all hall sensor output and magnetic fields are perfectly linear and symmetric.

	
Perfectly symmetric output from each sensor	Virtually zero measurement error

We can introduce various kinds of common conditions that cause measurement errors. For magnetic encoders, these include variances in DC offset in sensor, variances in output amplitude from each sensor, variances in mounting symmetry and external high frequency noise.

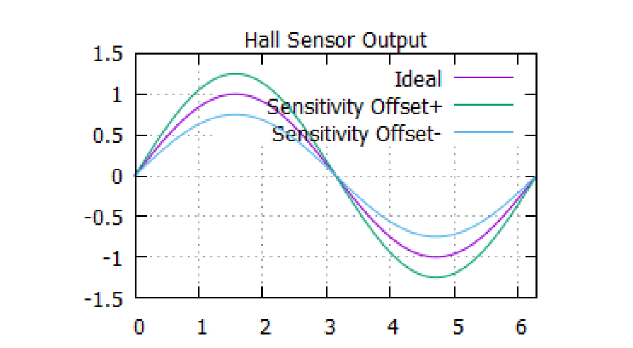
Example 1. DC offset variance

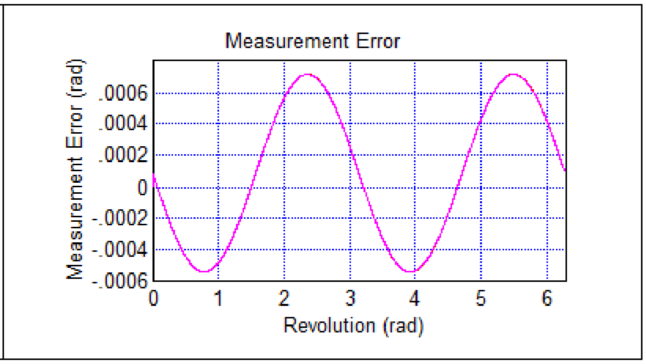
The sensor's quiescent voltage (steady state DC voltage) can be different depending on the exact sensor. If we apply a +1mV bias to Sensor0, a -3mV bias to Sensor5 and -1mV bias to Sensor6, the resulting measurement error is approximately 0.001rad = 0.057˚.

Example 2. Sensor output amplitude (sensitivity) variance

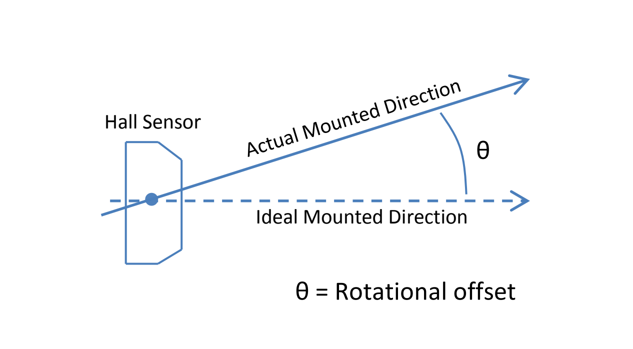
Each sensor's sensitivity, or output voltage response to input magnetic field can be different. Ideally, the hall sensor should output the exact same voltage amplitude given the same magnetic field. But chemical and manufacturing factors can vary the sensitivity, or amplitude by up to 0.5%. If we apply a +0.5% to Sensor0 and -0.5% Sensor5 and Sensor7, the resulting measurement error is approximately 0.0007rad = 0.040˚.

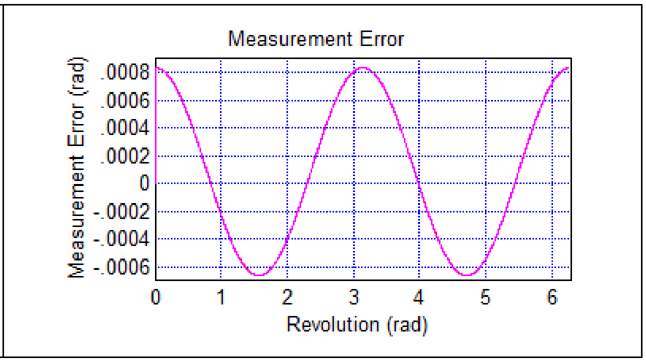




Example 3. Asymmetric sensor mounting

Dimensionally, if the sensors are not aligned correctly according to their ideal mounted direction, this can cause measurement error. Since the 8 sensors are mounted circularly around the magnet, each sensor should be faced in-line with its ideal position. We can simulate the measurement error given the rotational dimensional offset of each sensors mounted position. If Sensor0 was offset by .006rad and Sensor4 and 6 offset by -0.003rad, the measurement error is approximately 0.0008rad = 0.046 ˚.

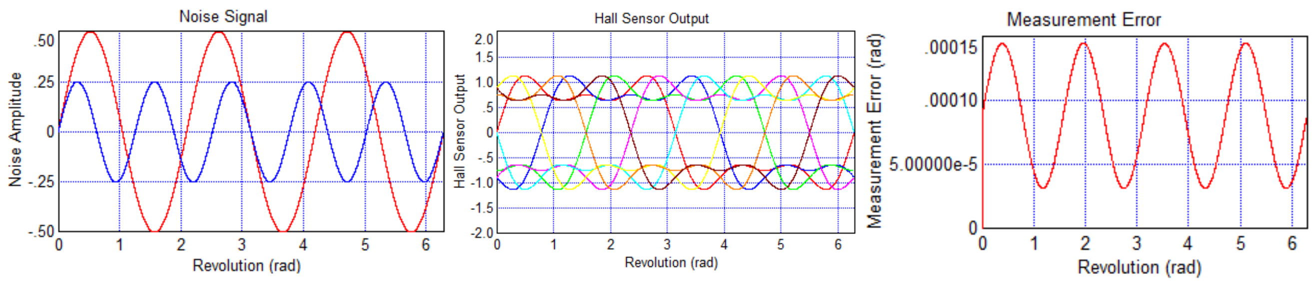




<u>Example 4. External high frequency noise</u>

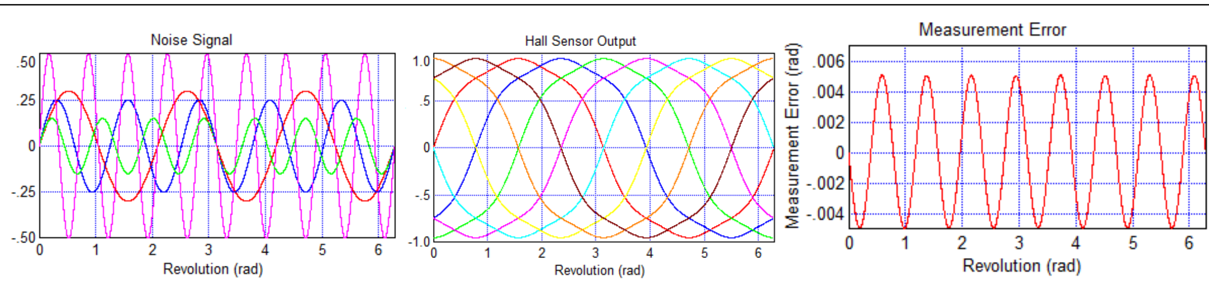
Traditionally, magnetic encoders are sensitive to external magnetic or electrical noise. The noise can severely affect the output from the hall sensors and cause measurement errors. We can simulate different kinds of external noise by introducing higher order disturbance to each sensor.

We can simulate an external noise directly onto the hall sensors to study their response and overall encoder calculation results. The simulated noise is a sinusoid and is calculated relative to the hall sensor amplitude A and frequency per revolution R. For example, this is a 0.5A amplitude with R/3 period frequency and 0.25A amplitude and R/5 period frequency noise:

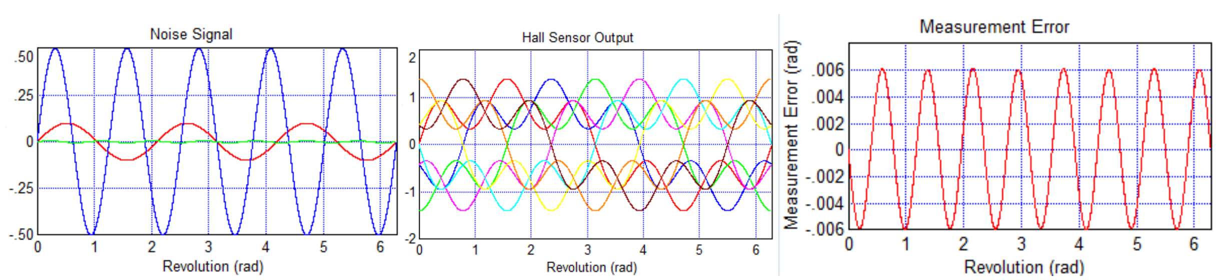


If we apply this noise to the system, the hall sensors response becomes very different. Even with this kind of non-ideal sensor output, the ABS-16 encoder can still maintain a measurement error of 0.00015rad = 0.0086˚.

By introducing a combination of noise signals, we can simulate the real-world operating environment of the ABS-16 encoder. The ABS-16 encoder's calculation algorithm can mathematically guarantee low measurement error under a variety of noise conditions.



Noise1–0.1A, R/3 Noise2–0.05A, R/5 Noise3-0.003A,R/7 Noise4-0.002A,R/9 Measurement error = 0.005rad



Noise1–0.1A, R/3 Noise2–0.5A, R/5 Noise3-0.005A,R/7 Noise4-0.001A,R/9 Measurement error = 0.006rad

Conclusion

The DMM ABS-16 magnetic encoder has a higher measurement error compared to a 2500line optical encoder. By comparing a sample data of measured error, and comparing with theoretical measurement errors for magnetic and optical encoders, we deduce that the optical encoder has an independent measurement error of 1 count per 10,000counts (0.036deg), and the ABS-16 encoder has an independent measurement error of 2.5~3 counts per 10,000counts (0.09~0.108deg).

But as various manufacturing and usage conditions changes the optical encoder’s mounting and environmental conditions, it is proven that its measurement error increases. So although the optical encoder has higher accuracy in ideal laboratory conditions, the actual accuracy during application is uncertain. It has been determined that the coupling between the two motors creates outside errors that cause overall measured error to be higher than that of the two independent errors combined.

By using simulation, the DMM ABS-16 encoder’s calculation algorithm can control measurement error even under severs manufactured variances and environmental operating conditions. The ABS-16 encoder has slightly lower accuracy characteristic, but its ability to supress outside disturbances is much more beneficial to the reliability, longevity and consistency of the servo motor, thus is a more suitable selection for the majority of motion control applications.

References:

(1) Renishaw plc. White paper: The accuracy of angle encoders (88692). 2015.
(2) Zettlex UK Ltd. http://www.zettlex.com/articles/optical-encoders-accurate-think/.

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