Accurate Measurement Of Angle Position At High Angular Velocities

Don Payne
Magnetic Sensors Corporation, 1365 North McCan Street, Anaheim, CA 92806

Presented at EMSA 2004, Cardiff University, July 7, 2004

Abstract

Error sources in measurements of angle position under static conditions often contribute inaccuracies that are unacceptable whenever precise position control is important. Time delays are another potential source for significant errors whenever determination of position is important at high rates of angular velocity. This paper presents an analysis of a method of accurately measuring a reference position, or index, at high engine RPM's. These conditions are generally necessary in instrumentation for evaluation or control of magnetic sensors used in ignition timing for the purpose of minimizing exhaust emissions.

Details are provided describing the construction and operation of a measurement system to enable convenient determination of angle position with an error of ±0.01º at circumferential surface speeds of up to 37.5 meters-per-second. This dynamic error is equivalent to the static error in a 15-bit encoder. A detailed error analysis is included.

Keywords: Accurate angle measurement; Ignition timing; Angle position; Angular velocity; Index mark

1. Introduction

1.1 *Need for accurate angle measurement at high angular velocities.*

The regulations of the United States Environmental Protection Agency (EPA) that are commonly referred to as the Tier II requirements [1] impose stringent emission standards for engines that use fossil fuels. The need for much more precise control of fuel injection and ignition timing to satisfy these requirements demands accurate measurement of crankshaft position. As an example, one of the diesel engines for locomotives [2] has a timing wheel that is almost 0.7 meters in diameter, and the system requires a sensor that provides a timing signal accurate to within ±0.05° at speeds to over 1,000 RPM.

Inasmuch as the sensor must provide a reliable signal in a harsh environment (including temperatures to 125°C) throughout the engine's 20-year lifetime, a magnetic sensor was specifically designed for this application.

1.2. *Example of errors at high speeds*

The requirement for the diesel locomotive engine's crank angle sensor is to detect the center of a tooth on a 90-tooth timing wheel within ±0.05°. The ±0.05° is equivalent to ±0.3mm at the circumference of the 0.7 meter wheel. This requires very tight control of the components and processes for static determination of position, yet the dynamic requirements pose even more demanding control of these factors.

A 15-bit encoder can provide the necessary accuracy for static operation and at low speeds; however, at 1,000 RPM the tangential velocity is over 37 meters per second, and 0.05° is crossed in less than 8 microseconds. A very fast optical encoder can respond within a few microseconds, yet this application requires response times that are a small fraction of a microsecond. No encoder could be found that provides a response suitable for accurately measuring events that occur this rapid.

While the requirements imposed on the sensor in this application require very stringent control of the sensing device itself, it is especially difficult to demonstrate that the sensing device actually satisfies the requirements. That is, even though the sensing device must be very good, the test equipment must be very, very good. Test equipment are typically required to have performance characteristics at least ten times more restrictive than the accuracy of the equipment being evaluated. The purpose of this paper is to describe test equipment that is suitable for applications such as the crank angle sensor.

2. Sensor description

The sensor is an especially characterized version of a common variable reluctance sensor [3] consisting of a solenoid coil that is wound around a ferrous pole piece. A rare-earth magnet at one end of the coil provides a strong magnetic field that extends through the pole piece and out of the cylindrical sensor to the timing gear teeth. The passing gear teeth vary the reluctance of the coil and a voltage is generated; with amplitude more-or-less proportional to speed and the frequency exactly proportional to speed. The instantaneous magnitude of the alternating voltage passes through zero as the center of the tooth passes very close to the centerline of the sensor. Ensuring that the zero-crossing is close to the middle of each tooth was an important factor in the sensor's design, and it continues to be a crucial factor in the tight control of the manufacturing process for the sensor.

The centerline of one of the teeth on the timing gear is identified as an index mark for crank angle position, and the zero-crossing of the voltage resulting from passage of that tooth is used by the electronic control unit (ECU) as a timing signal.

3. Fixture requirements

The formidable task for the test equipment, then, is to provide an accurate measurement of the phase angle between the passing of the exact centerline of the tooth and the zero-crossing of the voltage that is more-or-less coincident with the passage. This measurement must have a total error band that is a small fraction of the ±0.05° error allowed for the sensor because any measurement errors will reduce the effective error band of the sensor itself. If the measurement error is ±0.02°, for example, then the sensor itself must be accurate to within ±0.03°. Inasmuch as the ±0.05° total error allowed includes the effect of temperature variations from -40°C to 125°C, any tightening of the error band causes severe restrictions on the sensor's accuracy. The ±0.05° total error band also includes the effect of 1.5 mm variations in the air gap between the face of the sensor and the surface of the passing timing gear teeth. Moreover, this measurement error must include the errors introduced by slight variations in positioning of the sensor in the test fixture during different installations and by different operators.

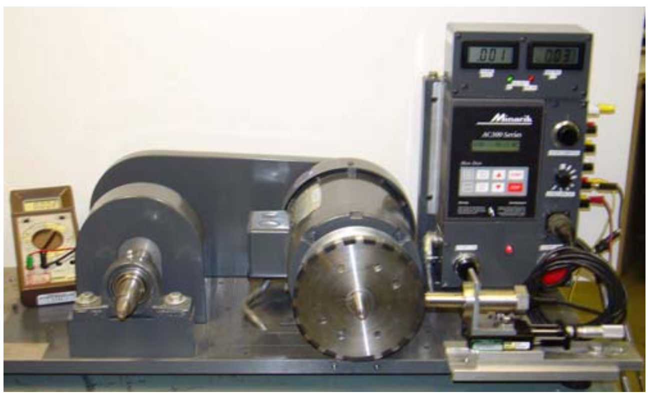

Figure 1. Test fixture

The difficulty of designing and manufacturing a sensor that provides the required accuracy increases dramatically as the performance requirements tighten, therefore it is very important that the test equipment errors be as small as possible. That is, if the measurement errors are a large portion of the allowable error band, then the actual requirements for the sensor in this application will be prohibitive.

4. Test equipment operation theory

Like all elegant solutions, the principle of operation is simple. If a pulse train can be generated so that the rising edge of the pulse is coincident with the tooth center passing the centerline of the sensor and the falling edge of the pulse is coincident with the sensor output's zero-crossing, then the pulse width will be proportional to the angle between those two events. That is, the duty cycle is directly proportional to the angle; with 360° equal to 100% duty cycle. Since the average voltage of a pulse-width modulated (PWM) signal is directly proportional to the duty cycle. then the average voltage is directly proportional to phase angle. Significantly, the average voltage is directly proportional to the angle at all speeds.

Referring to the block diagram shown in Figure 1, an optical switch generates an index pulse whenever the timing gear passes the precise center of the critical tooth. This index pulse sets a flip-flop, so that the output of the flip-flop goes high. When the sensor output later goes negative, a zero-crossing detector sends a pulse to the flip-flop to reset it and the output of the flip-flop then goes low. The flip-flop output remains low until the next index pulse occurs, which then initiates another cycle. The output from the flip-flop is consequently a PWM signal that is directly proportional to the phase angle.

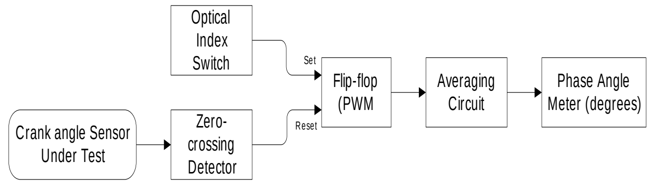

Figure 2: Test fixture block diagram

A passive resistor-capacitor circuit averages the PWM signal from the flip-flop. An active Butterworth-filter circuit further smoothes undulations in the averaged signal, and adjusts the scaling factor so that the output voltage is the digital equivalent of the phase angle. A digital panel meter then accurately displays the phase angle.

Although the operating principle is simple, actual implementation to achieve the required accuracy requires very careful selection of the test equipment components and the operating procedures.

5. Contributions to errors and worst-case error analysis

5.1. *Mechanical Positioning:*

The accuracy of the positioning of the sensor relative to the center of the index tooth is limited by the accuracy of the micrometer that is used in verifying the critical dimensions. The micrometer is certified NIST traceable to within ±0.0127 mm, which is 4.17% of the ±0.3 mm (±0.05º) error band.

5.2. *Optical Switch:*

An optical switch with 30 nanosecond rise and fall time and the shortest propagation delay was chosen to provide an index mark for the test fixture. The propagation delay and the rise time of the optical switch was minimized by observing the effect of varying circuit parameters and then choosing the optimum values. The forward current of the optical switch is variable, and the output load resistor is also variable. Not having an absolute standard to identify precisely when the center of the tooth passed the center of the sensor at high speed, the zero-crossing signal from the sensor was used as a reference signal and the circuit parameters were varied to minimize the propagation delay. The Optek OPB665 was found to be the fastest of the OPB665-OPB668 series [4]. With 12VDC excitation, a 360-ohm resistor for providing forward current and a 750-ohm pull-up resistor at the output yielded the shortest delay and the fastest rise time.

5.3. *Flip-flop propagation delay:*

The time delay from the beginning of the rise of the signal from the optical switch to the beginning of the rise from the output of the flip-flop register (MC14013B) was measured to be 90 nanoseconds [5], which is 0.57% of the 15.9 microsecond error band. This time delay was observed to be independent of the gear speed.

5.4. *Flip-flop rise/fall times:*

` The rise time and the fall time were measured to be 50-nanoseconds each, and they are independent of gear speed. Inasmuch as the effect of the rise time on the pulse duty cycle is cancelled by the fall time, there is no significant error caused by these factors. That is, the average value of a PWM signal is independent of the rise and fall times if those times are equal.

5.5. *Delay in zero-crossing detector:*

The delay from the negative-going zero-crossing to the fall time at the output of the flip-flop register was measured to be 300 nanoseconds, which is 1.89% of the specification limit.

5.6. *Flip-flop output offset from rail:*

The maximum offset of the MC14013B from either the positive or negative rail is measured to be less than 50 mV. This represents 0.42% of the 12-volt Vcc, and thus amounts to a gain error of 0.42% maximum.

5.7. *Scaling factor:*

Inasmuch as the output of the PWM averaging circuit has a sensitivity of 360° for 12 volts (30° per volt), 1.67 mV represents 0.05° on the 90-tooth, 0.7 meter timing wheel. If a 20-tooth test wheel that has the same tooth dimensions as the timing wheel is used for measuring the phase angle, the sensitivity will be increased by a factor of 4.5 so that 7.5 mV represents 0.05°. The smaller test wheel has other advantages for use in a test environment due to the reduced size and inertia. The wheel will, of course, be operated at 4.5 times as high an angular velocity as the locomotive engine's timing gear, yet the results will be essentially the same.

Since 7.5 mV represents 0.05°, a scaling factor of 20:3 will yield a digit-for-digit relationship between the output voltage and the phase angle. Two precision 1% resistors are used to establish this gain, therefore the maximum error contribution for the scaling factor will be 2%.

5.8. *Amplifier offset:*

The scaling amplifier (OPA2277PA) has an offset of 50 µvolts maximum [6], which is amplified by the factor of 20:3, so its error contribution may be as high as 333 µvolts or 0.33% of the specification limit of ±0.050 volts (±0.05°).

5.9. *Filter offset:*

The filter op-amp (another OPA2277PA) has an offset of 50 µvolts maximum and it is not amplified, so its error contribution may be as high as 0.05% of the specification limit of ±0.05°.

5.10. *Digital Panel Meter:*

The Martel DPM 2000 series [7] has an accuracy of 0.1%.

6. Error Summation:

The total sum of errors (using the extreme value analysis, or EVA, method) in the error budget is within 10% of the specification limit of ±0.05°. Accordingly, this detailed analysis indicates that the testing method will meet the requirements for accurate measurements of the phase angle of the crank angle sensor.

Error Source	Error Contribution
Mechanical positioning	4.17%
Flip-flop propagation delay	0.57%
Zero-crossing delay	1.89%
Flip-flop offset from rails	0.42%
Scaling factor	2.00%
Scaling amplifier offset	0.33%
Filter offset	0.05%
Digital panel meter	0.10%
Total error (as % of ±0.05° error band)	9.53%

Table 1. Contribution of Error Sources

Inasmuch as the EVA method assumes the unlikely condition that all of the errors may be the worst case in the same direction, the root-sum-of-squares (rss) method is generally used where there are a large number of contributions to errors. In this instance, the rss error is 5.06%.

6.1. *Test results*

Thirty crank angle sensors were manufactured and subjected to extensive process capability testing to validate this testing method. All thirty sensors were tested at each of six different speeds. The phase angle was measured for each sensor at three different airgaps (minimum, mid-point, and maximum) at each speed. In addition, ten sensors were tested in this manner by three different operators two times on two occasions separated by an interval of several weeks. The test equipment was completely disassembled during this interval to introduce any errors that might be introduced in misalignment during maintenance and calibration of the test equipment over its lifetime.

The extensive data (over 1,500 data points) were statistically evaluated using several techniques to ascertain the validity of this crank angle measurement method. Much of this data gathering process was, of course, for the purpose of evaluating the sensors themselves. That is, the results of the tests were also used to determine the performance characteristics of the sensors under various operating conditions.

All of the 1,080 data points taken by the three operators on the ten sensors were within ±0.01º of each other for the same operating conditions. This includes any positioning errors due to misalignment of the sensor during the six installations (two times by each of three operators). The misalignment errors surely were a significant part of the ±0.013 mm that represents ±0.01º, yet their magnitude has not been determined.

A detailed gage repeatability and reproducibility (Gage R&R) analysis using the Xbar and R method yielded a Gage R&R (% Tolerance) of 0.23%, which is very good (considering 10% was the worst case acceptable).

6.2. *Conclusion*

The phase angle measurement method whereby the PWM signal voltage is averaged to obtain an analog of the phase angle between two events has been demonstrated to be an accurate way to determine the phase angle of timing signals on rotating shafts at circumferential surface speeds of up to 37.5 meters-per-second to an accuracy of ±0.01º. This technique should prove useful in testing other critical timing applications, especially for high performance engines. Moreover, it will be suitable for evaluating sensor types other than variable reluctance devices; for example, Hall-effect speed sensors.

References:

[1] U.S. Environmental Protection Agency; Regulatory Impact Analysis (EPA420-R-04-007, May 2004)

[2] D. Machalaba, R. E. Silverman, GE Unveils Cleaner Locomotive To Meet Emissions Standards, Wall Street Journal, 23 December 2002

[3] Magnetic Sensors Corporation, Variable Reluctance Speed Sensor, 401031-00

[4] Optek Technology, Inc., Photologic Slotted Optical Switch Product Bulletin OPB665-OPB668

[5] ON Semiconductor, Dual Type D Blip-Flop Data Sheet MC14013B

[6] Burr-Brown Corporation, High Precision Operational Amplifiers Data Sheet OPA277

[7] Martel Electronics Corporation, Legacy Series Digital Panel Meter DPM 2000 Data Sheet

Biography:

Don Payne received his BSEE from the University of Washington in Seattle in 1956, and is a Registered Professional Engineer in California. Since 1995, he has been the Vice President of Engineering at Magnetic Sensors Corporation. Don has served as an expert in the subject of magnetics in federal court cases, and obtained fourteen patents for instrumentation techniques in the fields of medical, aerospace, automotive, and industrial process control.