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Accurate measurement of angle position at high angular velocities

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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 RPMs. 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 $\pm 0.01^\circ$ at circumferential surface speeds of up to 37.5 m/s. 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 m in diameter, and the system requires a sensor that provides a timing signal accurate to within $\pm 0.05^\circ$ at speeds to over 1000 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 $\pm 0.05^\circ$. The $\pm 0.05^\circ$ is equivalent to ± 0.3 mm at the circumference of the 0.7 m 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 1000 rpm the tangential velocity is over 37 m/s, and 0.05° is crossed in less than 8 μs. 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

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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 $\pm 0.05^\circ$ error allowed for the sensor because any measurement errors will reduce the effective error band of the sensor itself. If the measurement error is $\pm 0.02^\circ$, for example, then the sensor itself must be accurate to within $\pm 0.03^\circ$. Inasmuch as the $\pm 0.05^\circ$ total error allowed includes the effect of temperature variations from -40 to $125\,^\circ$C, any tightening of the error band causes severe restrictions on the sensor's accuracy. The $\pm 0.05^\circ$ 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 (Fig. 1).

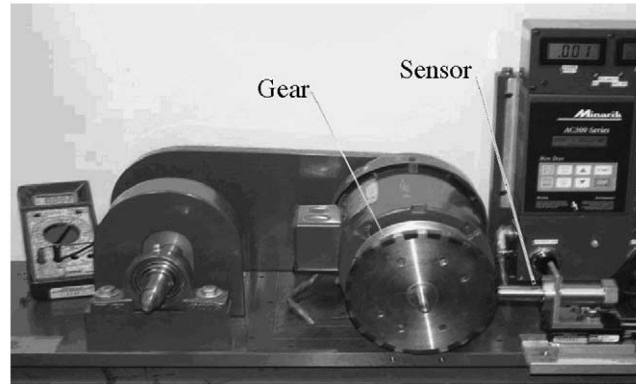

Fig. 1. Test fixture.

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 Fig. 2, an optical index 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. The sensor is identified in Fig. 2 as the crank angle sensor under test. 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.

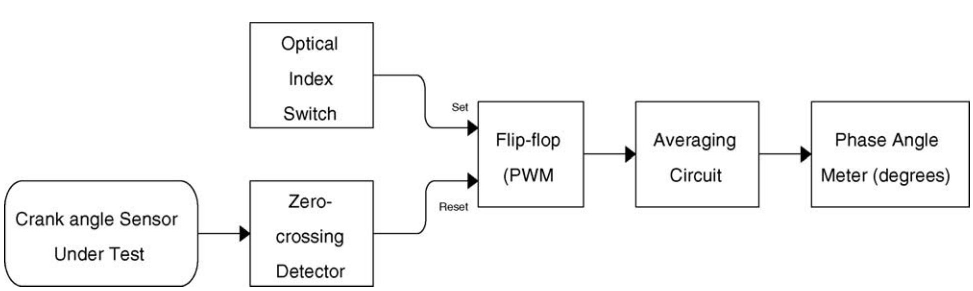

Fig. 2. Test fixture block diagram.