How to Implement Comparators for Improving Performance of Rotary Encoders in Industrial Drive Applications

Introduction

Optical encoders are the most popular type of feedback encoders due to their precision, high resolution, and strong resistance to electromagnetic interference (EMI). These optical sensors provide an electrical signal, typically in the form of a pulse train which can be decoded to obtain information relating to motion, direction, and position.

These encoders generally consist of a certain combination of the following types of devices: trans-impedance amplifiers, analog to digital converters (ADCs), and comparators. To understand how each of these devices works to make the encoder function properly, it will be important to understand the mechanical function of these encoders as well.

Incremental Encoders

There are generally two types of optical rotary encoders -- absolute and incremental. The output of digital incremental encoders consists of two square waves, each 90 degrees out of phase from one another. These square wave outputs are typically produced as a digital output from a comparator, which receives its input signal in the front end by an optical sensor. In a typical incremental optical encoder, an LED will direct light rays through a lens to focus the light. On the encoder shaft, there will be two tracks with gratings 90 degrees offset from one another. As the light from the LED gets shown through the openings of these gratings as the motor shaft rotates, the light will be directed onto a photodiode array.

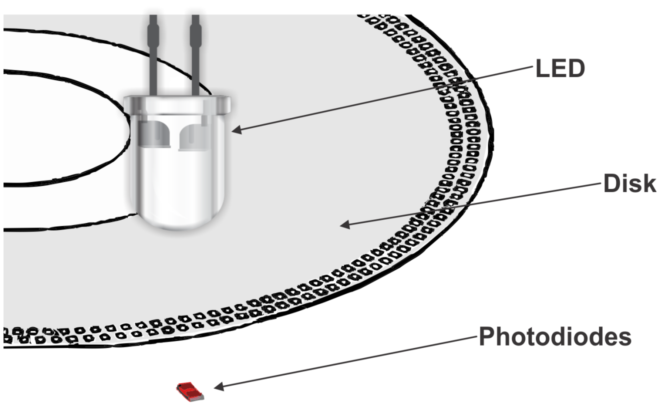

Figure 1. Rotary Motor Shaft Gratings

The photodiode array is typically connected to a trans-impedance amplifier to convert the current passed through the photodiode into a voltage. The result is two triangle or two sine waves (depending on the grating shape), each 90 degrees out of phase from one another -- we can call these signals A and B. These signals are then typically passed through an amplifier to increase the gain and offset the voltage to fall within the common mode range of a comparator. Most devices implement the gain stage within their transimpedance amplifier as well. The comparator is then used to digitize these analog voltage signals into square waves and level shift them to the appropriate standards for TTL logic.

In some cases, a second comparator stage can be used to drive HTL or RS-485. Typically, push-pull type comparators are used in these applications to avoid the need of a pullup resistor which can slow down the response time of the comparator. A high voltage, push-pull device such as the TLV1805 could be used to help drive the signal to HTL logic levels.

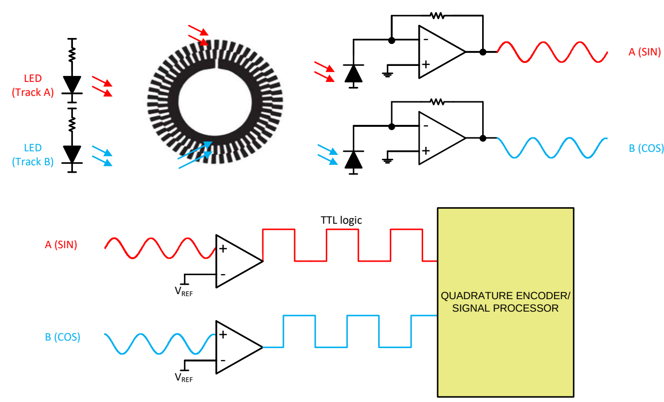

Figure 2. Simplified Incremental Encoder Scheme

Interfacing to Digital Incremental Encoders

These square waves are then fed into a signal processor that can decode the square wave pulse trains into useful information such as direction and speed using a quadrature encoding scheme. This signal processor is typically located inside the servo drive to which the incremental encoder is connected.

By looking at every edge from signals A and B, 4 different positions from one grating of the disc can be generated. Depending on which square wave from signals A and B is leading, the encoder will increment or decrement the count by one. The servo drive then uses the incremental count to calculate the motor shaft angle.

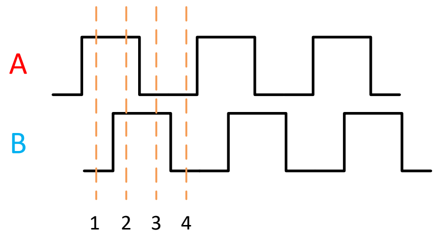

Figure 3. Quadrature Encoding Scheme

The resolution of this position in incremental encoders depends on the number of gratings or periods per revolution on the motor -- also known as the line count. The max signal frequency you should expect to see is the line count multiplied by the rotational speed of the shaft in hertz:

$$MAX\ \ SIGNAL\ \ FREQUENCY = LINECOUNT(N) \times RPM \times \frac{1}{60} \quad (1)$$

How to Implement an Interface to SIN/COS Encoders

There are many ways to use and interface the SIN/COS signals that are generated. One of these methods is by using two high-speed sampling ADCs. The ADCs will look at the sine and cosine signals A and B, and take the arc-tangent between the two signals to produce the phase difference between the two signals. By sampling at least 4x the signal frequency, a quadrature pulse encoder counter can be created strictly through software. To obtain high resolution positional information, ADCs need to sample signals A and B continuously which results in an increase in power consumption. While ADC's can provide very high resolution for positional feedback encoders, the cost and the power consumption that it draws may not always be an ideal solution for some customers.

Comparators can be used to create a digital incremental signal to calculate a course angle position, as the comparators will be used to monitor the SIN/COS signals and convert them to digital square waves. As long as the comparator switching threshold is faster than the max signal frequency, using only comparators to calculate the position of the motor shaft is feasible. The max switching frequency of a comparator is defined as:

$$MAX\ \ SWITCHING\ \ FREQUENCY \approx \frac{1}{\frac{1}{2}t_r + \frac{1}{2}t_f + t_{plh} + t_{phl}} \quad (2)$$

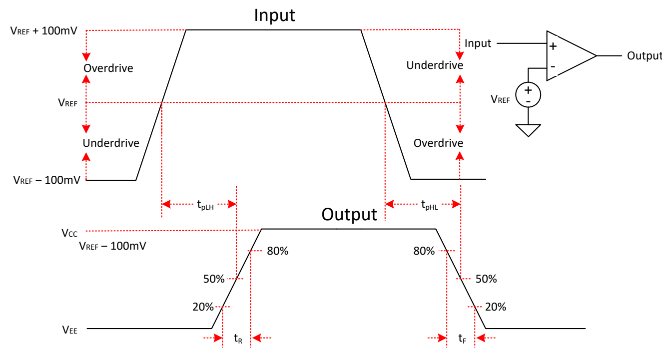

Figure 4. AC Timing Response

It is important to note that the propagation delay can vary greatly depending on certain specs such as input amplitude, common mode threshold, and the overdrive/underdrive of the input signal. Take the possible variation of the propagation delay into account when selecting and designing in a comparator for this application.

As stated previously, the max signal frequency that can be expected can be calculated by multiplying the line count with the rotational speed of the motor (N x RPM*1/60). The bit resolution of the encoder is defined as:

$$2^x = 4 \times N \quad (3)$$

where x is bit resolution, and N is the linecount of the encoder. The linecount is multiplied by 4 because there are 4 different positions that can be calculated within each increment of the linecount. A typical incremental encoder could have a line count of 2048, with the motor shaft running at 3000 RPM (50Hz). This translates to a max signal frequency of 102.4 kHz and a 13-bit resolution , where

$$BIT\ \ RESOLUTION = \frac{\ln(4 \times N)}{\ln(2)} \quad (4)$$

Texas Instruments offers several dual comparators that can handle this max switching frequency such as the LM393 or LM2903, which has a max switching frequency of 800kHz.

While a device like the TLC3702 (Max Switching Frequency = 108kHz) could theoretically be used in an application with a max signal frequency of 102.4kHz, it is important to note the time it will take for the signal processor to encode the signals into useful information, as well as the time it takes to generate any sort of correctional response to the motor. A comparator must be designed into the system with a general guideline that it can handle at least 3x the max SIN/COS signal frequency.

Incremental encoders can also have a third channel or track with a single grating or slot that is used as a zero reference marker for the device -- typically denoted as 'Z'. Without this zero reference, the incremental encoder can only report a change in angle within one rotation once power is connected to the encoder. In other words -- if the signal processor only receives information from signals A and B, it can only calculate the direction and the speed of the motor. When power is connected to an encoder with a zero reference, an initialization pulse to reference the encoder will be generated. After this initial pulse, the encoder will begin either incrementing or decrementing the count so that the signal processor can decode the information to give a specific position that the motor is in.

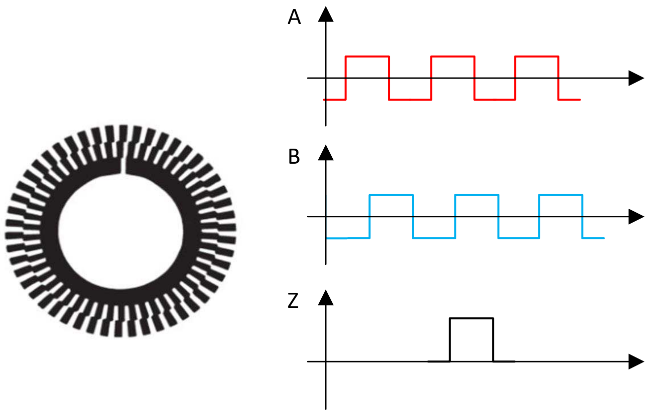

Figure 5. Zero-Reference Signal

Alternatively, quad-channel versions of comparators can be used if signals A and B are being viewed differentially to help mitigate any environmental noise that could affect the signals. Other channels of the comparator could also monitor the zero reference signal or even the light density and integrity produced by the LEDs. Texas Instruments quad differential comparators line of the LM339 or LM2901 (Max Switching Frequency = 800kHz) could be an appropriate choice to monitor more than just the SIN/COS signals A and B.

Using Comparators in an Absolute Encoder Scheme

While a solution to create an incremental encoder using only comparators can be achieved, higher resolution encoders with higher line counts would drive up the cost of the comparator significantly due to the requirement for higher speed and faster switching thresholds.

Another solution to calculate the position of the motor shaft is to combine the two solutions discussed previously to generate an absolute encoder with interpolated angle position. In an absolute encoder scheme, the position of the motor shaft is always known regardless of whether the encoder is powered on or not. Comparators will still take the SIN/COS signals from tracks A and B and digitize them into a quadrature encoder pulse counter, while dual ADCs will sample the SIN/COS signals every time the current count is changed. Typically, the PWM cycle time is 8kHz to 32kHz, which will require a lower sample rate and lower power ADCs in comparison to the method that uses dual high speed ADCs. With the phase interpolation from the ADCs and the line count generated from the comparators, an interpolated angle position can be created.

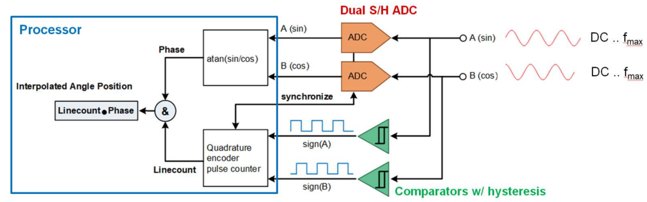

Figure 6. Combined Comparator + ADC Solution

For a 16 bit resolution on a motor shaft, this combined solution only needs to have a line count of 32 and a max switching frequency of just 8 kHz. In comparison, the method using only comparators would need a linecount of 16834 to reach a 16 bit resolution for position. For the same level of accuracy as the combined ADC + comparator solution, the comparator only method would need to have a max switching frequency of at least 4MHz (assuming the motor shaft is running at 15000 RPM). A device such as the TLV3502 (Max Switching Frequency = 76.9 MHz) would need to be used to achieve this high of positional resolution using only comparators.

Typically in absolute encoder schemes, comparators are used to monitor the zero reference signal via a battery backup. Therefore, in cases where power to the encoder is disconnected, the comparator running off of the battery backup will still track the zero reference signal so that the position of the motor shaft will always be known.

In short, the combined ADC + Comparator method can provide the same level of resolution as the method using only comparators, while requiring a much smaller switching frequency for the comparators. The solution can still be low power at the expense of having to do some additional signal processing with low sampling ADCs. A cost-optimized comparator such as the TLV7032 (Max Switching Frequency = 167kHz) can be used for this application while also providing the benefits of being a nano-powered solution (I_Q= 315nA), and would be very appropriate to use as part of the battery backup scheme for the absolute encoder.

Conclusion

It is important to understand the power consumption needs as well as the max incremental signal frequency of the encoder's photo diode output signals to implement an incremental or absolute optical encoder using comparators.Texas Instruments has a large line of comparators that can fulfill the different implementations of these types of encoders. If an incremental encoder is needed where power consumption is the most critical specification, a nano-powered device such as the TLV7032 or TLC3702 can be used to digitize the SIN/COS signals A and B.

Standard comparators such as the LM2901 or LM393 could also be used for encoders with slightly higher resolution without sacrificing on cost. If even higher resolution is needed, a device such as the TLV3502 could be used if the solution using only comparators to calculate the positional information is implemented.

Alternatively, using comparators in an absolute encoder scheme to track the line count and ADCs to calculate the phase difference between signals A and B could be used to achieve the same high resolution but with a switching frequency that is much lower. This method also benefits from typically having a battery backup solution monitoring the zero reference signal with a low power comparator, providing positional information of the motor shaft at all times.

Listed below are a list of comparators that Texas Instruments recommends to be suited for optical encoder applications. Many of these devices have the added benefit of being offered in both leaded and space-saving packages.

Table 1. Alternative Device Recommendations

DEVICE	CHANNELS	MAX SWITCHING FREQUENCY	IQ PER CHANNEL (uA)
TLV7032	2	167 kHz	0.3
TLV3502	2	76.9 MHz	3200
TLV3202	2	9 MHz	40
LM2901	2	800 kHz	200
LM393	2	800 kHz	200
LM2903	4	800 kHz	200

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