ANALOG DEVICES

AN-263
APPLICATION NOTE

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Resolver-to-Digital Conversion – A Simple and Cost Effective Alternative to Optical Shaft Encoders

by John Gasking

INTRODUCTION

Ever since man invented the wheel, we have wanted to know, with varying degrees of accuracy the position of that wheel. This measurement of angular position is a craft that has been refined through the ages and accelerated as production and control methods have become more sophisticated. Most forms of motive power finish with a rotating shaft, the most popular example being the electric motor, and even linear motion is produced by mechanically converting that rotary motion with screw threads, cranks, etc. The basis, therefore, of most mechanical positioning systems is the measurement of the shaft angle. The Greeks taught us many centuries ago how to deduce position from angles, today's computing power just allows us to make the deduction more quickly.

Angular and linear measurement – encoders and resolvers . . . to a digital output.

There are fundamentally two alternatives open to the designer when it comes to choosing the type of angular transducer, each with its particular characteristics. I shall describe the alternative so that, what I consider are the advantages of a resolver, can be better understood.

Encoders fall into two groups, incremental and absolute. Incremental encoders simply count the passing of a division of the circle and give pulsed outputs that allow you to store that count and know its direction of rotation. This is known as the A Quad B output system illustrated in Figure 1, the direction is deduced from the occurrence of the edges of the A and B pulse trains. An "A" 0 to 1 transition occurs before a "B" transition with one direction of rotation and vice versa for the opposite rotation. A datum pulse is generated synchronously with A and B as the shaft rotates through zero. Incremental encoders usually produce these pulses from photo-electric devices, which precludes them from use in radiation hazardous areas such as may be required by military and aerospace applications.

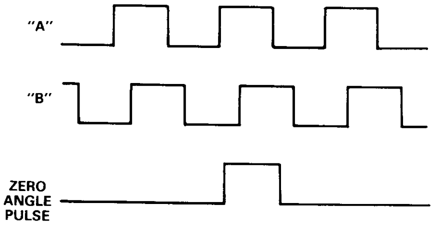

Figure 1.

Two disadvantages of incremental encoders are that the position is not known on "power up" and electrical interference can cause false counts.

Absolute encoders, as their name implies, give a parallel digital output that is generated from a pattern that is on a rotating disc attached to the shaft. The sensors used can be electrical contacts or a photo-electric system. Various codes are available, binary and Gray being the most popular. Very high resolutions and accuracies are available, 16 bits (20 arc seconds) and beyond. These are at very high cost, $1000's, and have the problem of parallel data transmission if the encoder is remote from the measuring electronics.

Probably one of the major reasons for the use of encoders is that it is obvious how they work and they give a digital output. Resolvers on the other hand, are a little less understood and the conversion appears complex. Recent advances in our conversion techniques and manufacturing technology makes application so simple that a complete understanding becomes less important.

The resolver is a rotating transformer whose output analog voltages are uniquely related to its input shaft angle. It is, therefore, an absolute position transducer with 0 to 360° of rotation.

The resolver as an angle measurement transducer has a number of advantages. Firstly, the resolver is a robust mechanical device that can withstand severe environments of dust, oil, temperature, shock and radiation. Secondly, being a transformer it provides signal isolation and a natural common-mode rejection of electrical interference. This feature coupled with the fact that only four wires are necessary for the angular data transmission, makes it unique in angle measurement and ideally suited to the harsh world encountered in the heavy manufacturing and aerospace industry. Today, brushless resolvers are available that have no slip ring connections to the rotor, which greatly increases their life and reliability.

The resolver can be positioned where the angle needs to be measured and the electronics can be positioned where the digital output needs to be, in the card frame with the processor.

There are two methods of using a resolver to obtain output voltages related to the shaft angle.

In the first method the rotor winding (Figure 2) is excited by an alternating signal and the output is taken from the two stator windings. As the stator windings are mechanically disposed at right angles, the output signal amplitudes are related by the trigonometric sine and cosine of the shaft angle. Both the sine and cosine output signals have the same phase as the original excitation signal, only their amplitudes are modulated by sine and cosine as the shaft rotates.

The second method of obtaining an output signal uniquely related to shaft angle is to excite the two stator windings. When the two stator windings are excited by two alternating signals that are in phase quadrature to each other, then a voltage is induced in the rotor winding whose amplitude and frequency are fixed but whose phase varies with shaft angle. Consider Figure 2. When the shaft aligns the rotor winding R_1R_2 with the stator windings S_1S_3 the rotor output signal will be at a maximum of the 0° phase excitation signal. When the rotor windings R_1R_2 align with the stator windings S_2S_4 the output signal will be at a maximum of the 90° phase excitation signal. At angles between these two positions, the phase of the output signal will vary linearly with angle from 0° to 90° phase. By rotation of the shaft through the full 360°, the phase of the output rotor signal will itself vary from 0° through 90°, 180°, 270° to 360°, i.e., back to 0° phase.

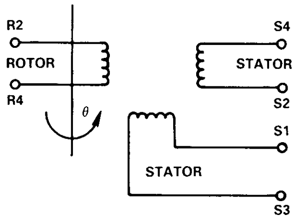
RESOLVER WINDINGS

Figure 2.

DIGITAL CONVERSION

Most intelligent robots and numericaly controlled machine tools use digital computers as the calculation and memory element of the system. Therefore, in order that the computer understands the situation, all the angles being measured must be translated into digital words.

In order to fully appreciate the advantages of the tracking resolver-to-digital converter, it is necessary to understand the major alternatives.

Apart from the tracking converter, there are two other methods of conversion widely used in industry. Both methods have some severe weaknesses as the demands of industry for high accuracy increases.

The alternatives to the tracking converter have until now been cost effective, however, with the improvements in our techniques, the cost of the converter has reduced to the point that many users are making a reappraisal and switching to the tracking converter.

The most widely used method at the present time is the method known as the "Phase Analog Technique". This method adopts the mode of stator winding excitation by two signals in phase quadrature shown in Figure 3. In order to measure the shaft angle, accurate measurement of the phase of the rotor signal with respect to the excitation signal is necessary. A block diagram of such a scheme is shown in Figure 3.

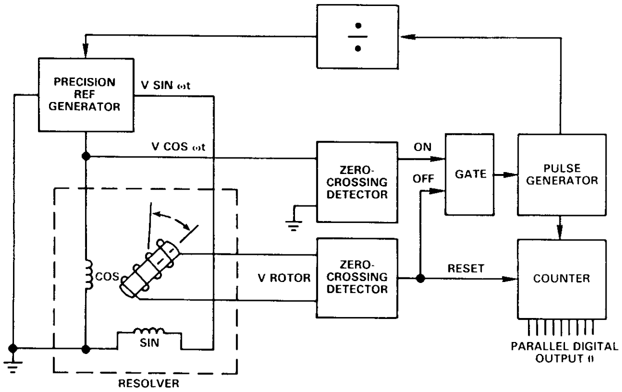

Figure 3.

In essence, the time interval between a zero crossing of the sine or 0° excitation signal and the zero crossing of the rotor signal is measured (see Figure 4). This is done by counting the numbers of pulses from the original reference clock oscillator that occur between the two zero crossings. By varying the division ratio between the reference clock oscillator and the two excitation generators, the resolution to which this measurement is made can be varied.

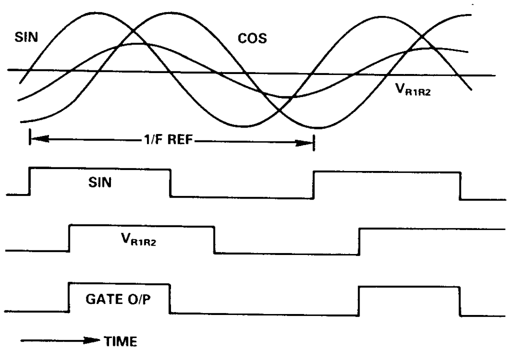

Figure 4.

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*Footnote: The circle is divided into 360 degrees, it is then further subdivided into minutes and seconds. So that minutes and seconds of arc were not confused with minutes and seconds of time, the subdivisions are always referred to as arc minutes and arc seconds. Sixty arc seconds = 1 arc minute. Sixty arc minutes = 1 degree.

This division ratio has little effect on accuracy as that is determined by the accuracy to which the zero crossing intervals can be measured. The first and most obvious source of error is the electrical noise generated by the environment of the resolver causing noise on the rotor signal which makes the zero crossing point become indeterminate. The second and more subtle source of error comes from variations in the excitation. Any variation of the relative amplitudes or phases of the two excitation signals directly influences the phase of the output signal. As most systems use a square wave clock with integrated circuit dividers, very precise filtering of the signals is required to obtain the pure sinusoidal signal necessary. Such accurate filters are complex and it is difficult to obtain a good temperature versus phase coefficient. Any harmonic distortion of either or both the excitation signals will also affect the phase of the rotor signal. The summation of all, these errors limit the accuracy of the "Phase Analog" approach to about 10 bits or 21 arc mins.

The second most widely used method of resolver-to-digital conversion method is a sampling technique. There are many variations of this technique, however, in essence, they all make a sample of the sine and cosine output signals of a rotor excited resolver. The sample of the signal amplitudes is taken at a peak of the reference input amplitude and converted to digital signals by an A/D converter. The resulting digital words are used as a memory address to "look-up" the shaft angles in a processor.

The difficulties with such an apparently simple method comes from its total inability to deal with noise. If a noise disturbance occurs on the signal lines at the time of sampling, then a wrong answer results. If the noise only results in a single wrong reading, then the frequency pass band of the servomotor drive system acts as a filter and little error results. If, however, the noise is severe, then the errors can become unacceptable.

TRACKING RESOLVER-TO-DIGITAL CONVERISON

The tracking conversion techniques used in all our converters overcomes all the difficulties experienced by the other methods. The new 1S series of converters in particular compete with the other methods cost wise and yet provide superior accuracy, noise-immune operation. The basic method of operation and connection is shown in Figure 6.

A tracking converter operates ratiometrically, that means that it is only concerned with the ratio of the sine and cosine outputs of a rotor excited resolver. As the resolver acts as a transformer, any excitation waveform distortion or amplitude variation appears in the correct ratio on both sine and cosine and has little effect on accuracy. A tracking converter contains a phase demodulator and therefore frequency variation and incoherent noise do not affect accuracy. Tracking converters can operate with any reference excitation from square waves to triangular waves with only minor accuracy variation. Common-mode rejection is achieved by the natural isolation of the resolver, this combined with the integration of the tracking loop makes an angular-to-digital conversion system with excellent noise immunity.

As a tracking converter uses an internal servo system that contains integration in the control loop, there is little degradation of accuracy even at high input revolution rates up to more than 40,000 revs per minute.

APPLYING THE RESOLVER AND TRACKING CONVERTER

The most common misapprehension about resolvers concerns their working voltages and frequencies.

As the resolver is a linear transformer in which the primary winding rotates inside the secondary windings, it behaves as a normal transformer. There is a transformation ratio that is fixed within certain frequency limitations specified by the manufacturer. The rotor excitation or reference input can be varied to give the stator output voltages that are required to be directly connected to the converter inputs.

Variation of the reference frequency can cause changes in the phase angle between the stator rotor or signal outputs and the reference or rotor input. As the tracking converter is tolerant to both phase and amplitude, often no correction is needed. However, when using the 1S64 or 1S74 series of converters which provide a high quality velocity signal in addition to the digital position, it is essential that the phase shift is zero. This can be achieved by selecting the appropriate frequency, or using a resistor/capacitor phase shift network on the converter's reference input. (See also section "Maximum Lead Length Between Resolver and Converter".)

REFERENCE FREQUENCY

Converter tracking rate, that is the maximum speed up to which the input angle can be followed by the converter, is related directly to the reference frequency.

A rotor excited resolver when rotating gives an output that is a modulated carrier signal.

$V_{S153} = \sin \omega_2 t \, V_R \sin \omega_1 t$

where V_R = peak reference voltage

ω_1 = reference frequency in radians/sec.

ω_2 = shaft rotational frequency in radians/sec.

In order to convey the information ω_1 must always be greater ω_2.

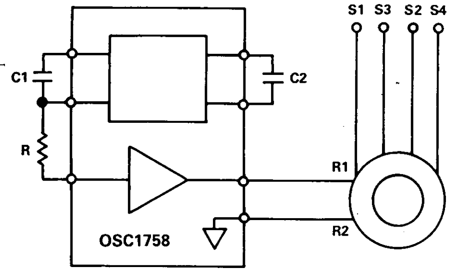
REFERENCE OSCILLATOR

We currently offer a hybrid power oscillator, OSC1758, which is capable of supply 1.4VA.

The OSC1758 is in fact in two sections namely an oscillator and a power amplifier. They are separately accessible.

The frequency of the device is determined by two capacitors C1 and C2.

Remember that the tracking conversion technique is very tolerant on amplitude and frequency stability and, therefore, any drift in the capacitors will not unduly affect the



FREQUENCY = 5kHz

RESOLVER ROTOR IMPEDANCE (Z_{SO}) = $850 + j\,1250$

$|Z_{SO}|$ = $\sqrt{850^2 + 1250^2}$

= 1511Ω

TRANSFORMATION RATIO = 0.5 = T.R.

RESOLVER PHASE SHIFT @ 5kHZ = −5°

REFERENCE VOLTAGE REQUIRED (V_R) = 2/T.R. (NOTE 2V rms IS REQUIRED BY THE 1S CONVERTER)

V_R = 2/0.5 = 4V rms

REFERENCE CURRENT = $\frac{V_R}{Z_{SO}} = \frac{4}{1511} = 2.6\text{mA}$

RESISTOR R = $\frac{37.5 \times 10^3}{V_{OUT}} - 5350\Omega$

= $\frac{37.5 \times 10^3}{4} - 5350$

= 4025Ω

CAPACITORS C1 = C2 = $\frac{1}{F_{OSC} \times 10^5}$ FARADS

= $\frac{1}{5.0 \times 10^3 \times 10^5} = 0.002\mu\text{F}$

Figure 5.

accuracy or performance of the overall system. However, it is suggested that high grade silver mica capacitors are used with a temperature coefficient of less than 50ppm/°C.

Connection to a typical brushless resolver is shown in Figure 5.

From the above it can be seen that the drive requirement is well within the capability of the OSC1758 and that many more resolvers could be powered from the same source when multichannel angular measurements are necessary.

MAXIMUM LEAD LENGTHS BETWEEN RESOLVER AND CONVERTER

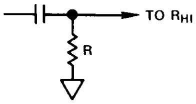
The question is often asked as to the maximum length of lead between the resolver and the converter.

The answer is that this distance can be very long indeed providing the following simple precautions are taken.

1. It can be shown mathematically that as long as the phase shift between Sine/Cosine and Reference signals is zero, the additional errors due to capacitive effects of the interconnecting lead will be zero. The phase shift can be zero'd either by selecting the frequency at which zero phase shift occurs across the resolver or by introducing a phase lead or lag into the reference input to the converter.

   Simple phase lead and lag circuits are shown below.

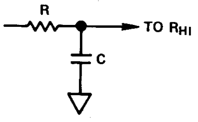
   PHASE LEAD



$$\text{Lead} = \text{ARC TAN}\,\frac{1}{2\pi fRC}$$

where f is the frequency.

PHASE LAG



$$\text{Lag} = \text{ARC TAN}\,2\pi fRC$$

2. Ensure that the reference frequency is such that:

   $$\frac{1}{2\pi fcL}$$

   is greater than X where:

   f = reference frequency

   c = Lead capacitance per metre of the cable.

   L = Distance between resolver and converter in metres.

   X = The reactive component of the resolver output impedance.

3. Ensure that the attenuation of the signal (sine/cosine) does not lower the voltage appearing at the inputs to the converter by less than 10% of the nominal voltage specified.
4. Use individually screened twisted pair leads for sine, cosine and reference signals. On four-wire output resolvers driving into converters which have only a "Sine", "Cosine", and "A GND" input, the common connection should be made at "A GND" on the converter.

Provided that the above precautions are followed, it is possible to transmit the angular data hundreds of metres without loss of accuracy and with the very considerable advantage of high-noise immunity.

CONCLUSION

The objective of this note was to indicate the simplicity and advantages of using resolvers in the cost effective measurement of the position. While such measuring devices are used within sophisticated control systems, recommendations beyond the digital interface are outside our brief as a component manufacturer, except that we recognize that they exist and have requirements of the transducer systems. To this end, we offer the best performance we can and publish with our data the Transfer Functions and dynamic specifications that allow system designers to calculate our converter's performance within their control circuits.

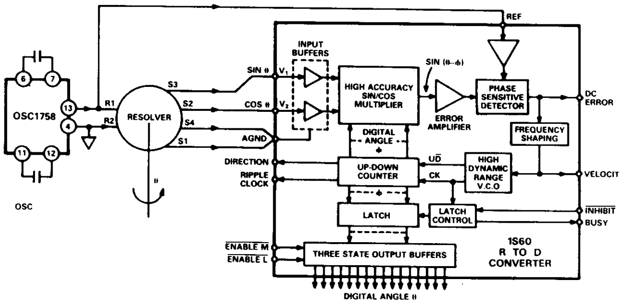


Figure 6.