Control Sciences Incorporated

Resolvers as Velocity and Position Encoding Devices

Introduction

The shaft angle transducer is a fundamental component in modern control technology. It is difficult to define a mechanical system in aerospace or industry that does not have several axis of angular or linear motion. By employing direct coupling or a straightforward mechanical translation, a shaft angle can be used to monitor either type of displacement.

Encoding Methods

The following types of shaft angle transducers are common to the control industry:

Potentiometer
Incremental encoder
Absolute encoder
Resolver
Inductosyn™
Potentiometer

The potentiometer houses a circular ring of resistive material. A rotating contact is positioned on the resistive material according to the input shaft angle. The resistance between one end of the ring and the contact is proportional to the shaft angle. If a voltage is applied across the potentiometer, the voltage at the contact varies according to the shaft angle. This voltage can be routed to an A/D converter to derive a digital shaft angle.

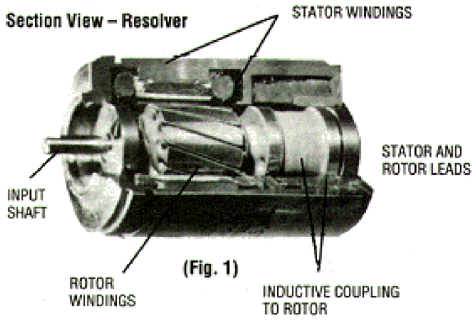
Incremental Shaft Encoders

Encoders directly convert shaft angle to a digital format. Optical encoders for industrial applications consist of a shaft-mounted disc with concentric rings of alternate transparent and opaque segments. These segments block or pass light from an LED or incandescent light source to a group of photocells buffered to produce usable output logic levels. Incremental encoders are less expensive but result in volatile systems because they must be re-zeroed or reset after even a brief loss of power.

Absolute Encoders

Absolute optical encoders are similar to incremental types, but employ a ring for every order output bit. These rings normally produce a gray code to avoid ambiguity. In addition to photo detectors and buffers, units generally contain electronics to convert from gray to binary code.

Resolvers



(Fig. 1)

Resolvers resemble small rotors and are essentially rotary transformers designed so the coefficient of coupling between rotor and stator varies with the shaft angle. Fixed windings are placed on a laminated iron stack to form the stator, and movable windings are placed on a laminated iron stack to form the rotor. Usually resolvers have a pair of windings on a rotor and a second pair on the stator, positioned at right angles to each other. When a rotor winding is excited with an ac reference signal, stator windings produce ac voltage outputs that vary in amplitude according to the sine and cosine of shaft position.

Connection to the rotor is made by the brushes and slip rings, or inductive coupling. Resolvers using the inductive method are referred to as brushless types. The inductive (brushless) resolvers offer up to 10 times the life of brush types and are insensitive to vibration and dirt, therefore they are used in the majority of industrial applications.

The stator signals from a resolver are routed to a specialized type of analog-to-digital converter system known as a resolver-to-digital (R/D) converter. Commercially available models include both tracking and multiplexed types.

Inductosyns

The Inductosyn™ is an AC device whose signals behave much like those from a resolver. This device employs etched patterns that are placed directly on rotary or linear substrates. The devices operate on inductive or capacitive coupling between sets of the patterns to generate AC signals proportional to the sine and cosine of angle. The electronics required to convert the signals into digital format are similar to an R/D converter.

Comparing Techniques

Potentiometers are useful for accuracies in the 5% to 0.5% area and are the lowest cost device presented herein. Since they are subject to wear, their application is generally limited to consumer and low end industrial applications.

Incremental encoders are reasonably inexpensive. They are found extensively in industry, although their reliability is somewhat marginal in harsh environments. Discs can crack under shock, and condensation can cause output errors. Their volatile outputs can also limit acceptability in some applications.

Absolute encoders range from medium to high cost depending on resolution required. Like their incremental counterparts, they are somewhat limited by reliability considerations.
Inductosyns are relatively expensive but offer very high accuracies. Since they have virtually no moving parts to wear, they are very reliable. Support electronics is required to condition the drive and output signals of the device in addition to the Inductosyn-to-digital converter.

Resolver Based Systems

Three basic types of resolvers are common to aerospace and industry. These are the resolver transmitter (RX), the resolver differential (RD) and the resolver control transformer (RC). The difference between types has to do with the arrangement and number of windings used and whether the rotor or stator windings are used as the primary. The resolver transmitter is best suited for modern conversion techniques, therefore it will be designated as the principal transducer used for the balance of this presentation.

The Resolver Transmitter

Conventions

A schematic of the resolver transmitter is illustrated (fig. 2). By convention, the positive direction (increasing angle) of rotor motion is counter-clock wise when a resolver is viewed from the shaft end. Resolver manufacturers normally identify the zero angle mechanically with a scribe on the shaft and a corresponding arrow or dot on the housing. Typical equations are as follows:

E (S3-S1) = KE (R2-R4) SIN q

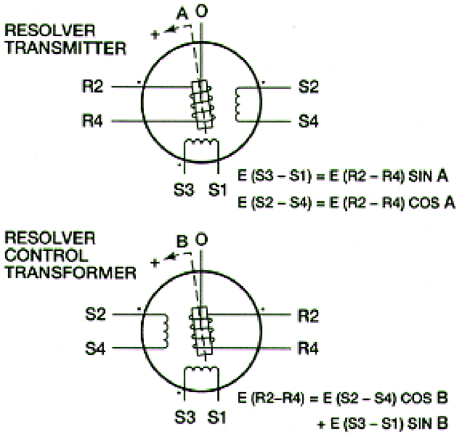
E (S2-S4) = KE (R2-R4) COS q

where E (R2-R4) = V sin wt
(ac excitation)

K = Transformation ratio
Of the resolver

q = Shaft angle of the resolver

Basic Trigonometric Law
SIN A COS B - COS A SIN B = SIN (A-B)



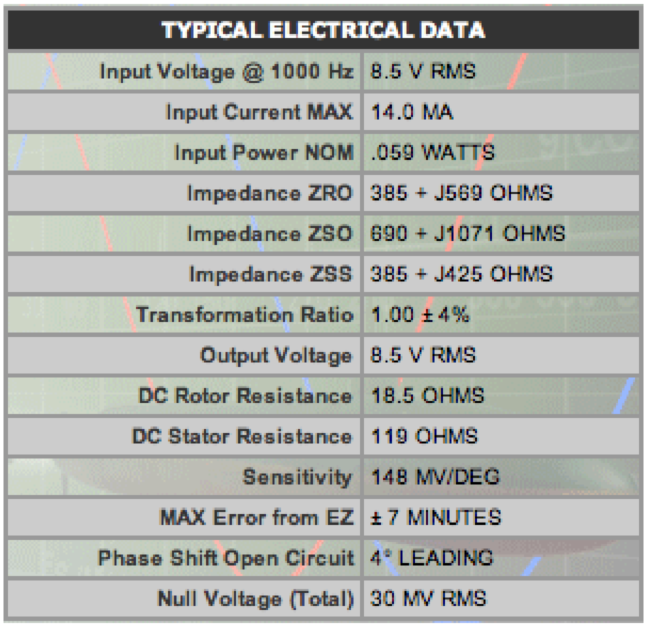
Equivalent Resolver Schematics
(Fig. 2)

Parameters

The most important electrical parameters of a resolver transmitter are the angular accuracy, input voltage, frequency of operation and transformation ratio. Phase shift is not normally critical except for fast moving systems and/or where higher resolution converters are employed. Rotor and stator impedances are not normally critical. Occasionally one will select low impedance values if resolver outputs are run over 200 feet. Higher values are selected to reduce the amount of excitation current required to drive the resolver rotor.

Sample Specifications

The following sample specification is given for a Harowe Model 11 BRCX-30-N-10B



TYPICAL ELECTRICAL DATA	
Input Voltage @ 1000 Hz	8.5 V RMS
Input Current MAX	14.0 MA
Input Power NOM	.059 WATTS
Impedance ZRO	385 + J569 OHMS
Impedance ZSO	690 + J1071 OHMS
Impedance ZSS	385 + J425 OHMS
Transformation Ratio	1.00 ± 4%
Output Voltage	8.5 V RMS
DC Rotor Resistance	18.5 OHMS
DC Stator Resistance	119 OHMS
Sensitivity	148 MV/DEG
MAX Error from EZ	± 7 MINUTES
Phase Shift Open Circuit	4° LEADING
Null Voltage (Total)	30 MV RMS

The Resolver-to-Digital Converter

The BAMS System

The accepted method of representing angular information in digital form is the "BAMS" (Binary Angle Measurement Systems). In this system, the most significant bit represents 180° , the next bit 90° , the next 45° , etc. The value of the least significant bit is then dependent on the resolution. The 12th bit value is 360° divided by 212 or 0.088° . An alternative BCD format is employed for display applications.

Basic Algorithm

The trigonometric law which forms the foundation for most resolver conversion methods is as follows:

$$\text{SIN A COS B} \pm \text{COS A SIN B} = \text{SIN (A} \pm \text{B)}$$

This law may be modified extensively to facilitate different implementations.

Example Implementation

To illustrate a simple application of the above formula, consider the two resolver systems shown below. The transformation ratio is 1.0 rotor to stator or vice versa. The output of resolver A is:

$$ES3\text{-}S = V \sin A$$

$$ES2\text{-}S = V \cos A$$

where V is the excitation voltage applied to the rotor. In effect, resolver A “multiplies” the input voltage by the sine and cosine of shaft angle.

The output of resolver B is:

$$E\ (R2\text{-}R4) = E\ (S2\text{-}S4) \cos B + E\ (S1\text{-}S3) \sin B$$

Resolver B acts as a control transformer, “multiplying” the input between S2-S4 by the cosine of its shaft angle B and the input from S3-S1 by the sine of angle B. If we now connect the V sinA output of resolver A to the S2-S4 input of resolver B and connect the V cosA output to the S3-S1 input of resolver B, the output of resolver B will then be:

$$E\ (R2\text{-}R4) = V \sin A \cos B + V \cos A \sin B$$

$$= V \sin (A + B)$$

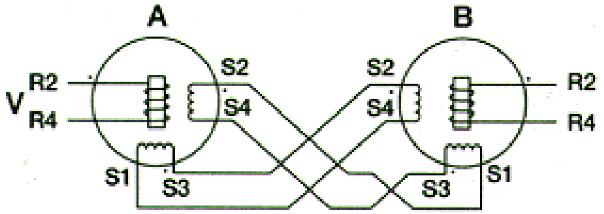
It will be more useful to reverse the polarity of the S3-S1 input to resolver B. The resulting output is now:

$$E\ (R2\text{-}R4) = V \sin A \cos B - V \cos A \sin B$$

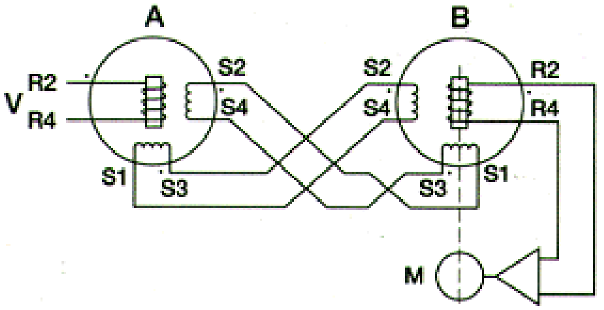
$$= V \sin (A - B)$$

If the rotor of resolver B is turned until the angle agrees with the angle of resolver A, it may be seen that the output of resolver B would go to zero.

If we added an error amplifier and a motor to shaft B, the position of shaft B would be continually driven to agree with the position of shaft A. This is a basic servo loop and also a close analogy to the function of a tracking resolver-to-digital converter.



$$E\,(R2_B - R4_B) = V_{\sin A \cos B} - V_{\cos A \sin B}$$
$$= V_{\sin (A - B)}$$

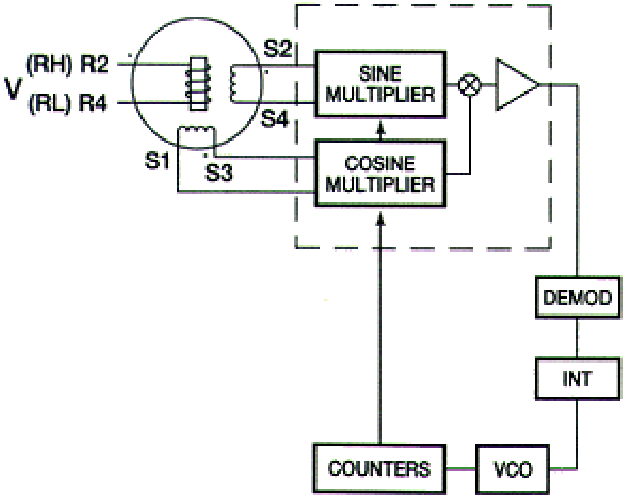


Basic Resolver Follow-up System

(Fig. 3)

The Tracking Resolver-to-Digital Converter

The tracking R/D converter performs a similar function in our basic control system example. Refer to the block diagram bellow (fig. 4). The tracking converter multiplies input sine and cosine values by cosine and sine terms, forms the difference, and “drives” its output angle until a null is reached.



Basic Solid State Follow-up (Tracking) System

(Fig. 4)

The function of resolver B is replaced by a solid state RC which performs the sine/cosine multiplying function and derives the difference angle. The shaft is replaced by a set of up/down counters which store angle B and control the sine/cosine multipliers in the solid state RC. The motor is replaced by a VCO (Voltage Controlled Oscillator) whose output "drives" the counters until input and output angles agree. The servo amplifier is replaced by a synchronous demodulator and integrator which provide a dc error signal to the VCO.

The tracking converter contains two integrators. The first is a conventional analog integrator, whereas the second is an incremental integrator implemented by the up/down counters. Since the tracking converter constitutes a closed loop system with two lags, it forms a type II servo system. The converter system exhibits negligible delays with velocity and only minor delays with acceleration.

The input to the VCO is proportional to velocity and the input to the integrator is proportional to acceleration. Both may also be provided as auxiliary outputs in addition to position information. In many cases, the velocity output may be used to replace tachometers.

Error Considerations

Manufacturers of resolver-to-digital converters usually do a good job of defining performance characteristics. Most spec sheets include reference to environmental changes that may be tolerated without compromising the stated accuracy of the unit. Examples are temperature range, reference voltage tolerance, power supply fluctuations, distortion, phase shift, etc. Indeed, tracking converters employing type II servo loops do exhibit high immunity to most environmental changes. However, the actual accuracy realized in a system using a particular converter type will probably be more affected by some environmental conditions than others, and it is important for designers to understand these effects before they can be confident of getting the expected results.

Phase Shift and Quadrature

One of the largest contributors to potential error is phase shift of the ac input (stator) voltages with respect to the converter reference (rotor) voltage. Phase shifts occur across the input resolver and in the converter itself. The net affect of phase shift is a change in the voltage gradient of the error voltage generated within the converter. This voltage is used to change the converter output to agree with a changing resolver shaft position.

Increasing phase shifts decrease the error gradient so that the converter will no longer be able to differentiate and react to small input changes. The result is seen as a reduction in accuracy, loss of sensitivity and repeatability and an increase in hysteresis.

Additional errors are caused by quadrature, or a signal which is 90° out of phase with the fundamental. Quadrature is divided into two components, static and dynamic. Static quadrature is generated by the resolver component and is relatively constant. Resolver spec sheets normally specify this value. Dynamic quadrature is also generated by the resolver as it rotates. The resultant quadrature increases with speed and is commonly called the "speed voltage."

Converters normally neutralize or reject quadrature, but when phase shifts are present, the quadrature rejection is significantly reduced. In this situation quadrature generates angular offsets and causes many converters to "hunt" or exhibit jitter in the LSB's.

Naturally, these conditions will be more pronounced in high resolution converters. Nominal phase shifts over 10° do not cause much problem until users attempt to hold accuracies better than 2 or 3 minutes of arc, which correlate to 14-bit, 16-bit or higher resolution. If phase problems exist with a converter/resolver combination, they will not show up when a resolver standard is used to check converter accuracy.

In practice, phase shift may be dealt with by shifting the reference phasing to a compromise value to minimize its affect or by including a "synthesized reference" in the converter. The latter allows up to 45° of phase shift and deals with both dynamic and static errors.

Velocity and Acceleration

Tracking converters will maintain accuracy up to rated resolver angular velocity. There is no "time of conversion" associated with this type of conversion as is normal with most A/D's. While designers do not have to allow extra tolerance for constant velocities, they must be aware of acceleration affects.

Converter spec sheets normally include reference to acceleration for 1 LSB error and/or unit KA (The Acceleration Constant). The first is not a limit on acceleration but a guide to assist designers in predicting the added error or lag generated while undergoing acceleration. Acceleration lag is linear, so twice the rating will generate 2 LSB's lag, etc. To find the lag for any acceleration in degrees, divide the acceleration of interest by the KA.

Obviously, the higher the acceleration constants are, the less lag will result for a particular system acceleration. The important thing to remember is that acceleration errors and static errors are additive, but they are only present while the system is undergoing a positive or negative acceleration.

Input Overvoltage

Another significant feature of resolver converters is the allowable input overvoltage or transient the inputs may be exposed to without damage. When specified, these may be as low as twice the rated input voltage or as high as ten times the rated voltage. The ability to withstand high voltages may be correlated to reduced failures in real world environments.

Inhibit

Manufacturers normally recommend a procedure for reading data from converters that employ an inhibit line. This line stops the converter from changing while data is read. The inhibit line is not a storage command but a freeze command. The actual time allowable depends on the velocity of the system and may vary between manufacturers. It is hard to predict just how long a user may hold this input beyond 10 microseconds. For safety, the shorter the better. Where this is a problem, users may add 3-state latches or choose one of several converters with 3-state outputs.

The Resolver Converter System

One of the most common questions a designer asks is “how do I select a resolver and converter type that I can be sure will work well together in my application?”.
The simple truth is both components have relatively flexible characteristics, and designers many times overspecify one or both to their detriment.

The most popular resolver for most applications is the brushless size 11 resolver as manufactured by several suppliers. The major difference between types offered is the transformation ratio (rotor-to-stator), the voltage and frequency specified and the impedance characteristics.

A good practice would be to talk to a resolver applications engineer before final selection, but one of the best recommendations is for designer to select a resolver that is in volume production. This practice will tend to result in the best price and delivery quotations.

Most size 11 resolvers have nearly flat response from 400 Hz to 10 KHz, so that designers do have a degree of flexibility in this area. Phase shift from rotor to stator is typically 7 degrees leading (stator to rotor) at 400 Hz and 10 approximately 2600 Hz which is a good choice for most applications (See Error Considerations).

Although the specified voltages (rotor and stator) are normally those used for test of the resolver, lower voltages will not cause significant errors.

The main desire is to retain the best signal-to-noise ratio possible so there is reason to stay close to those voltages recommended. However, lower voltages may be used to simplify oscillator design or accommodate a particular converter specification.

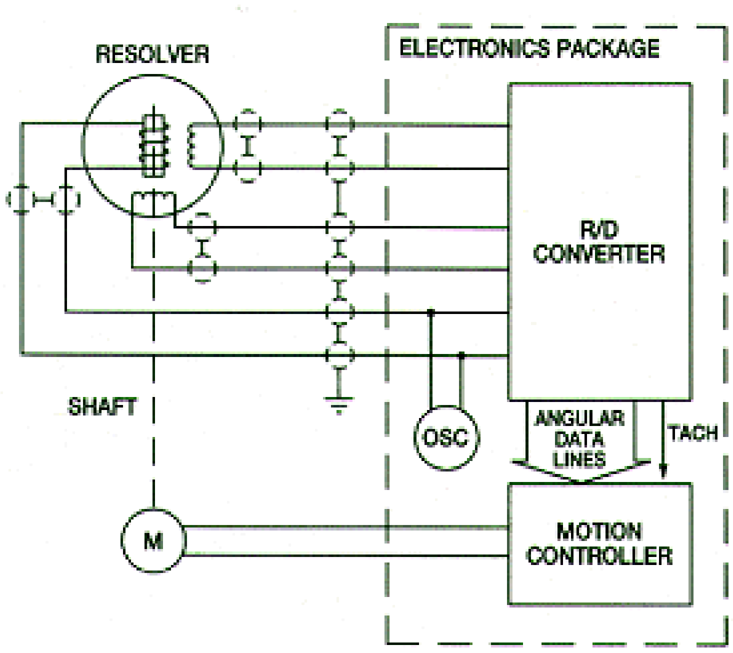
Rotor and stator impedance characteristics are not critical, but noise considerations dictate lower impedances for runs over 200 feet between resolver and converter.

Perhaps the most critical specification to observe is the matching of selected resolver stator voltage to the converter input. Most converters tolerate voltages 10% high and as much as 30% low without affecting performance. Since the rotor (reference) voltage is normally squared by a comparator to drive the demodulator in the comparator, it may vary a great deal without introducing errors (typically 10 to 100 volts rms.)

Converters are usually broadband, that is, many will work 400 Hz to 5000 Hz or higher without error. The only critical frequency is the lowest frequency anticipated. This dictates the cutoff frequency of the converter integrator and consequently limits the dynamic response of the converter, even if higher frequencies are used.

Finally, another area of flexibility is the waveform to be used. Most resolvers and converters operate well with sine, square or triangular waveforms.

In short, designers have a great deal of flexibility in matching resolvers and converters. Most resolver manufacturers select or alter characteristics to suit an application without much affect on cost or delivery. Similarly, most converter manufacturers can alter voltages, dynamic response or other characteristics.



Typical Resolver-Based Position Control System

(Fig. 5)

Summary

Resolvers are one of the most reliable components available to monitor shaft position. They are well suited to hostile environments and their performance does not deteriorate with time. They may be placed up to 500 feet from a system electronics package with a minimum of interconnect wiring. Resolvers offer infinite repeatability, provide absolute non-volatile outputs, and have a high degree of flexibility which simplifies matching them to converter electronics.

The combination of a brushless resolver and a tracking converter not only provides real-time position information but also can approximate the function of a brushless DC tachometer — providing accurate velocity information. The resolver/converter combination is then a powerful tool for the control industry.