

## Resolver-to-Digital Converters

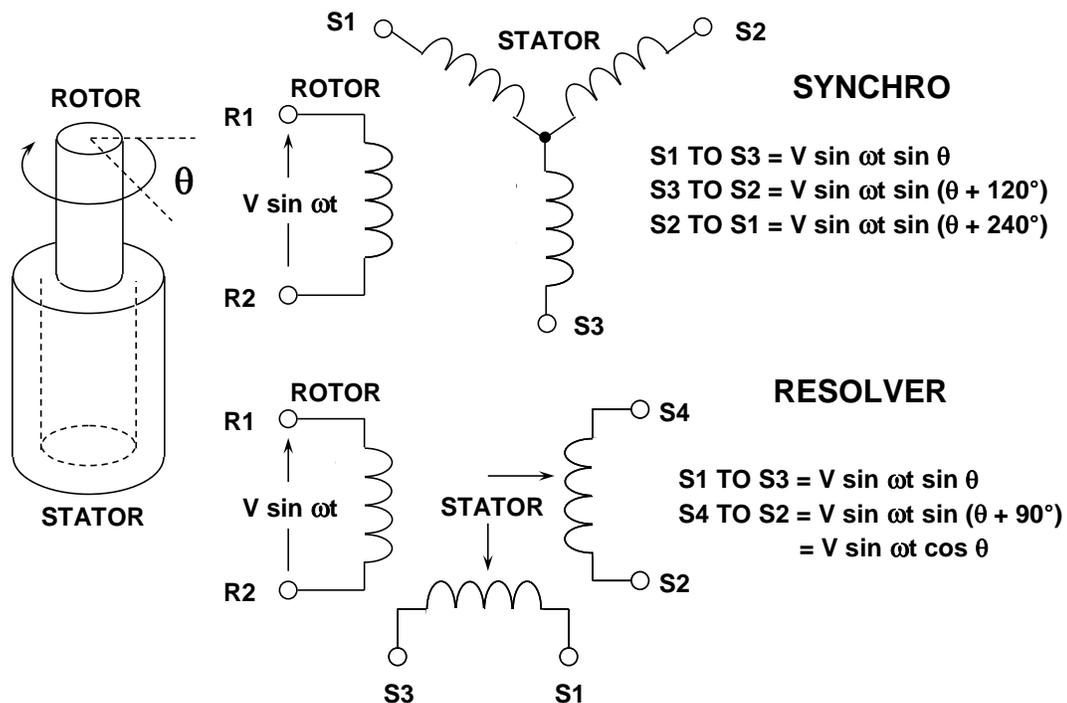
by Walt Kester

### INTRODUCTION

Machine-tool and robotics manufacturers use resolvers and synchros to provide accurate angular and rotational information. These devices excel in demanding factory and aviation applications requiring small size, long-term reliability, absolute position measurement, high accuracy, and low-noise operation.

### SYNCHROS AND RESOLVERS

A diagram of a typical synchro and resolver is shown in Figure 1. Both synchros and resolvers employ single-winding rotors that revolve inside fixed stators. In the case of a simple synchro, the stator has three windings oriented 120° apart and electrically connected in a Y-connection. Resolvers differ from synchros in that their stators have only two windings oriented at 90°.



**Figure 1: Synchros and Resolvers**

Because synchros have three stator coils in a 120° orientation, they are more difficult than resolvers to manufacture and are therefore more costly. Today, synchros find decreasing use, except in certain military and avionic retrofit applications.

Modern resolvers, in contrast, are available in a brushless form that employ a transformer to couple the rotor signals from the stator to the rotor. The primary winding of this transformer resides on the stator, and the secondary on the rotor. Other resolvers use more traditional brushes or slip rings to couple the signal into the rotor winding. Brushless resolvers are more rugged than synchros because there are no brushes to break or dislodge, and the life of a brushless resolver is limited only by its bearings. Most resolvers are specified to work over 2 V to 40 V rms and at frequencies from 400 Hz to 10 kHz. Angular accuracies range from 5 arc-minutes to 0.5 arc-minutes. (There are 60 arc-minutes in one degree, and 60 arc-seconds in one arc-minute. Hence, one arc-minute is equal to 0.0167 degrees).

In operation, synchros and resolvers resemble rotating transformers. The rotor winding is excited by an ac reference voltage, at frequencies up to a few kHz. The magnitude of the voltage induced in any stator winding is proportional to the sine of the angle,  $\theta$ , between the rotor coil axis and the stator coil axis. In the case of a synchro, the voltage induced across any pair of stator terminals will be the vector sum of the voltages across the two connected coils.

For example, if the rotor of a synchro is excited with a reference voltage,  $V\sin\omega t$ , across its terminals R1 and R2, then the stator's terminal will see voltages in the form:

$$S1 \text{ to } S3 = V \sin\omega t \sin\theta \quad \text{Eq. 1}$$

$$S3 \text{ to } S2 = V \sin\omega t \sin(\theta + 120^\circ) \quad \text{Eq. 2}$$

$$S2 \text{ to } S1 = V \sin\omega t \sin(\theta + 240^\circ), \quad \text{Eq. 3}$$

where  $\theta$  is the shaft angle.

In the case of a resolver, with a rotor ac reference voltage of  $V\sin\omega t$ , the stator's terminal voltages will be:

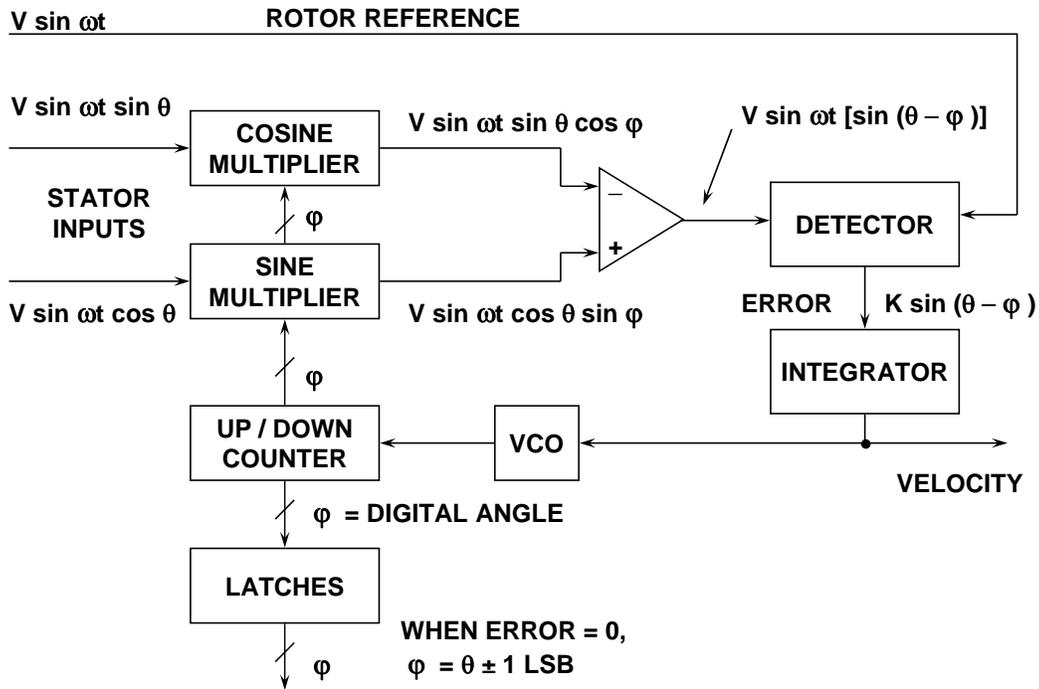
$$S1 \text{ to } S3 = V \sin\omega t \sin \theta \quad \text{Eq. 4}$$

$$S4 \text{ to } S2 = V \sin\omega t \sin(\theta + 90^\circ) = V \sin\omega t \cos\theta. \quad \text{Eq. 5}$$

It should be noted that the 3-wire synchro output can be easily converted into the resolver-equivalent format using a Scott-T transformer. Therefore, the following signal processing example describes only the resolver configuration.

**RESOLVER-TO-DIGITAL CONVERTERS (RDCs)**

A typical resolver-to-digital converter (RDC) is shown functionally in Figure 2. The two outputs of the resolver are applied to cosine and sine multipliers. These multipliers incorporate sine and cosine lookup tables and function as multiplying digital-to-analog converters. Begin by assuming that the current state of the up/down counter is a digital number representing a trial angle,  $\phi$ . The converter seeks to adjust the digital angle,  $\phi$ , continuously to become equal to, and to track  $\theta$ , the analog angle being measured.



**Figure 2: Resolver-to-Digital Converter (RDC)**

The resolver's stator output voltages are written as:

$$V_1 = V \sin\omega t \sin\theta \tag{Eq. 6}$$

$$V_2 = V \sin\omega t \cos\theta \tag{Eq. 7}$$

where  $\theta$  is the angle of the resolver's rotor. The digital angle  $\phi$  is applied to the cosine multiplier, and its cosine is multiplied by  $V_1$  to produce the term:

$$V \sin\omega t \sin\theta \cos\phi. \tag{Eq. 8}$$

The digital angle  $\varphi$  is also applied to the sine multiplier and multiplied by  $V_2$  to produce the term:

$$V \sin\omega t \cos\theta \sin\varphi. \quad \text{Eq. 9}$$

These two signals are subtracted from each other by the error amplifier to yield an ac error signal of the form:

$$V \sin\omega t [\sin\theta \cos\varphi - \cos\theta \sin\varphi]. \quad \text{Eq. 10}$$

Using a simple trigonometric identity, this reduces to:

$$V \sin\omega t [\sin(\theta - \varphi)]. \quad \text{Eq. 11}$$

The detector synchronously demodulates this ac error signal, using the resolver's rotor voltage as a reference. This results in a dc error signal proportional to  $\sin(\theta - \varphi)$ .

The dc error signal feeds an integrator, the output of which drives a voltage-controlled-oscillator (VCO). The VCO, in turn, causes the up/down counter to count in the proper direction to cause:

$$\sin(\theta - \varphi) \rightarrow 0. \quad \text{Eq. 12}$$

When this is achieved,

$$\theta - \varphi \rightarrow 0, \quad \text{Eq. 13}$$

and therefore

$$\varphi = \theta \quad \text{Eq. 14}$$

to within one count. Hence, the counter's digital output,  $\varphi$ , represents the angle  $\theta$ . The latches enable this data to be transferred externally without interrupting the loop's tracking.

This circuit is equivalent to a so-called type-2 servo loop, because it has, in effect, two integrators. One is the counter, which accumulates pulses; the other is the integrator at the output of the detector. In a type-2 servo loop with a constant rotational velocity input, the output digital word continuously follows, or tracks the input, without needing externally derived convert commands, and with no steady state phase lag between the digital output word and actual shaft angle. An error signal appears only during periods of acceleration or deceleration.

As an added bonus, the tracking RDC provides an analog dc output voltage directly proportional to the shaft's rotational velocity. This is a useful feature if velocity is to be measured or used as a stabilization term in a servo system, and it makes additional tachometers unnecessary.

Since the operation of an RDC depends only on the ratio between input signal amplitudes, attenuation in the lines connecting them to resolvers doesn't substantially affect performance. For similar reasons, these converters are not greatly susceptible to waveform distortion. In fact, they can operate with as much as 10% harmonic distortion on the input signals; some applications actually use square-wave references with little additional error.

Tracking ADCs are therefore ideally suited to RDCs. While other ADC architectures, such as successive approximation, could be used, the tracking converter is the most accurate and efficient for this application.

Because the tracking converter doubly integrates its error signal, the device offers a high degree of noise immunity (12-dB-per-octave rolloff). The net area under any given noise spike produces an error. However, typical inductively coupled noise spikes have equal positive and negative going waveforms. When integrated, this results in a zero net error signal. The resulting noise immunity, combined with the converter's insensitivity to voltage drops, lets the user locate the converter at a considerable distance from the resolver. Noise rejection is further enhanced by the detector's rejection of any signal not at the reference frequency, such as wideband noise.

The [AD2S90](#) is one of a number of integrated RDCs offered by Analog Devices (see [Synchro and Resolver to Digital Selection Tables](#)). The general architecture is similar to that of Figure 2. Further details on synchro and resolver-to-digital converters can be found in References 1, 2, and 3.

## REFERENCES

1. Dan Sheingold, *Analog-Digital Conversion Handbook*, Prentice-Hall, 1986, ISBN-0-13-032848-0, pp. 441-471. (*this chapter contains an excellent tutorial on optical, synchro, and resolver-to-digital conversion*).
2. Dennis Fu, "Circuit Applications of the AD2S90 Resolver-to-Digital Converter," [Application Note AN-230](#), Analog Devices. (*applications of the AD2S90 RTD*).
3. John Gasking, "Resolver-to-Digital Conversion: A Simple and Cost Effective Alternative to Optical Shaft Encoders," [Application Note AN-263](#), Analog Devices.

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