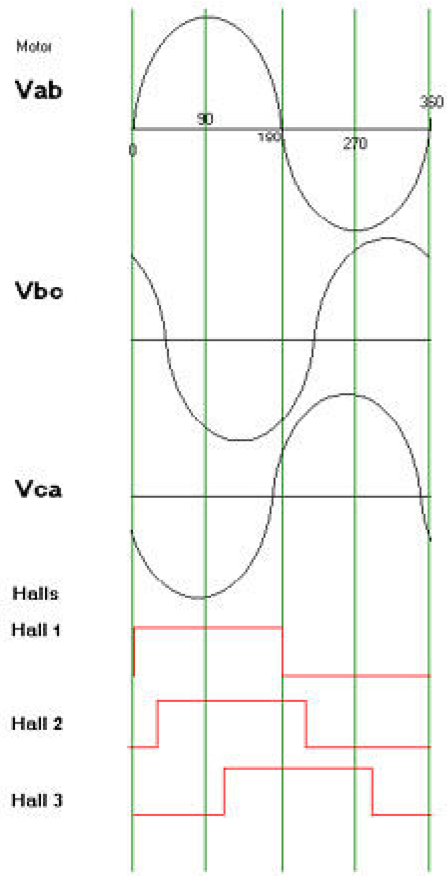
Feedback Devices Overview

Hall Effect Sensors

Hall effect devices are digital On/Off sensors constructed of semiconductor material used to sense the presence of magnetic fields. In brushless servomotors, they are used as position feedback when six-step commutation is employed.



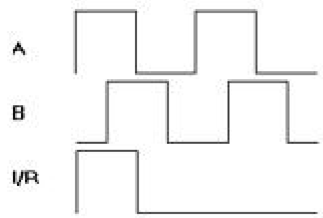
Some six-step drives incorporate this feedback for crude velocity sensing or course positioning. With sinusoidal current drives, they are sometime used along with incremental encoder feedback to give a course power-up position indicator. In servo drives, they are commonly used as current sensors to close the current loop. In other industry applications they are used for sensing the position of a crankshaft, cam, or other mechanical device.

In brushless servo motors, the halls are usually imbedded within the motor windings and sense the position of the rotor magnets. There is one sensor for each motor phase, aligned with the stator winding.

Incremental Encoders

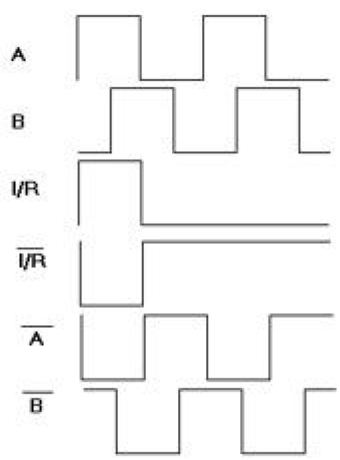
Encoders provide incremental motor position information via two channels, referred to as the A Channel and B Channel. These channels output a specific number of pulses for a unit of shaft motion. These pulses are typically generated within the encoder using an optical disk directly connected to the motor shaft. The disk has etchings on it that either transmits or blocks light passing through the disk. An optical transmitter and receiver sit on either side of the disk. The rotation of the disc (and motor shaft) interrupts light transmission from source to receiver, creating the pulses. The interruptions on the disk are called lines and result is the encoder's rating of lines-per-revolution (LPR), sometimes referred to as pulses-per-revolution (PPR).

The most popular of the encoders is the incremental TTL (transistor transistor logic output) type. The output is a digital pulse train with varying resolutions. Encoder resolutions of 50 - 5,000 LPR are standard from most vendors. Special line counts up to 100,000 are also available. Encoders provide A, B & Index or Reference signals. Channels A and B are 90° apart as shown below.



The encoder output can also have a compliment signal. The compliment signal aids in noise immunity. By detect the rising signal, or more positive going signal, the encoder resolution can be increased by a factor of 4. For example a 1024 line encoder with complimentary, or quadrature output, has 4096 counts per revolution.

Quadrature Channels
The two channels provide the same information (pulses per unit of motion), but have an electrical phase shift of 90º between each other. The 90º electrical phase shift between the two channels is referred to as "quadrature-encoded." Hence, the term "A-quad-B." The encoder output appears as a frequency, but the pulse rate is dependent on the motor's rotational velocity, not time. Since the two channels are phase-shifted by 90º, there are actually four states available per electrical cycle of these signals. The complimentary output signal is shown below.



The controller is able to receive four counts for position feedback for one line of motion of the encoder. The actual decode of the four position counts-per-line of the encoder is called "quadrature decode." Since the encoder signals A and B are phase shifted by 90º, it is easy to design electronics that recognize whether A came before B or B came before A, thus supplying directional information. It is also easy to calculate velocity by differentiation: dividing the number of pulses per unit time by the time.

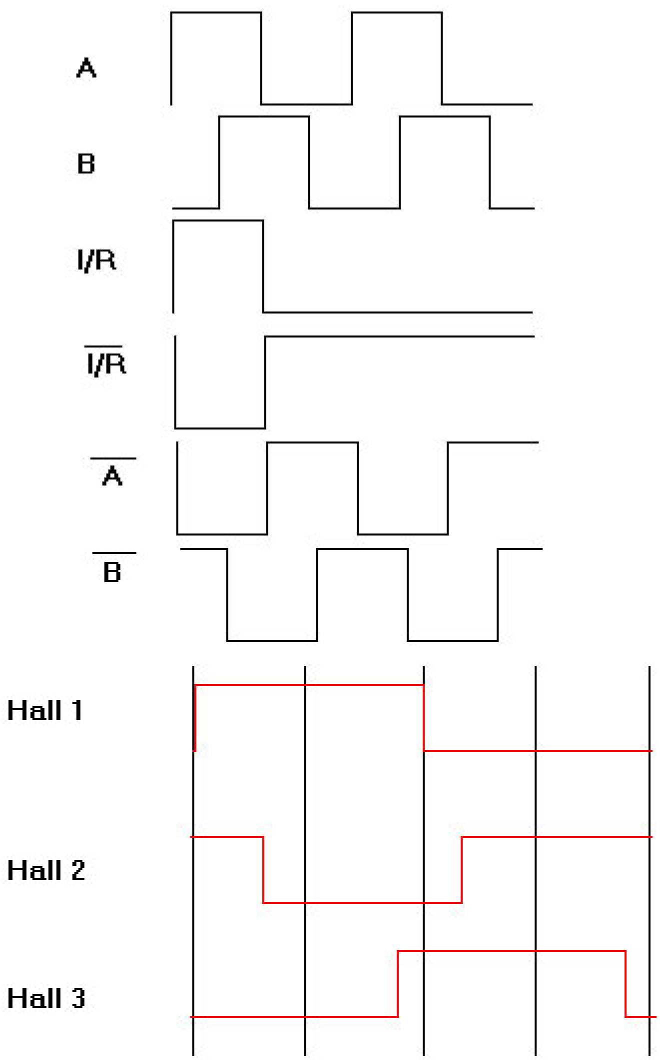
Marker Channel
Encoders are often provided with an additional channel called a "Marker" channel, Zero Pulse, or an "Index" channel. These are merely different names for the same function. This channel outputs one pulse-per-revolution

and is typically an extremely narrow pulse equating to roughly ¼ of the width of an A or B channel pulse, but can be wider. This is a reference position marker used for homing (absolute position reference) and commutation alignment.

Commutation Tracks

One challenge when using encoders for commutating a brushless motor is that they are incremental devices rather than absolute devices. At power-up with an absolute device (such as a resolver), the device transmits a code that is unambiguous to any position within its rotation. In other words, at power-up, the system knows the position of the motor shaft.

Encoders are incremental devices, meaning that there is no way to know exactly the position of the shaft at power up, only how far it has moved from its original position. This presents a problem with three-phase brushless motors in terms of commutation alignment. It is extremely important to establish the appropriate commutation angle within the controller. (Commutation refers to the alignment of the electromagnetic field to the permanent magnet fields to create optimal torque.) For this reason, encoders or motors are often provided with additional channels sometimes called "commutation tracks" or "Hall emulation tracks" which provide 1-part-in-6 absolute position information. The Hall channels can be synthesized in the encoder or can be discrete devices integrated in the motor windings. Commutation tracks (Hall channels) provide three digital channels that represent alignment to the A-phase, B-phase, and C-phase back EMF of the motor (shown below).

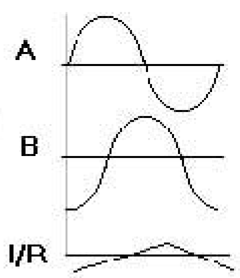


Differential Line Drivers
Since encoders are incremental devices, a loss or gain of a pulse creates system errors. Electrical noise is the single biggest factor in miss-counts. Transmitting the signals differentially provides the largest margin of noise rejection and the best signal fidelity. Some "less expensive" encoders only provide TTL or "Open Collector" signals.

Sine Encoders

Sine and Cosine Channels
Sine Encoders are very similar to incremental encoders so its helpful if the incremental encoder information is reviewed prior to this document. The difference between incremental encoders and sine encoders is simply that the A and B data channels are sent to the controller as 1 volt peak-to-peak sinewaves instead of the digital pulse format.

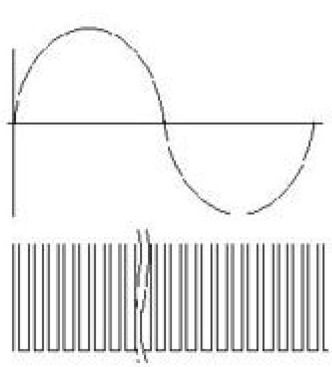
The sinusoidal wave output looks like:



Interpolation
One of the major advantages of the sine encoder is the ability to "interpolate" each complete sine wave, which greatly increases the system's resolution. The interpolation is accomplished by reading the value of the voltage of the A and B channels and performing an arithmetic calculation to determine the position within a sinewave.

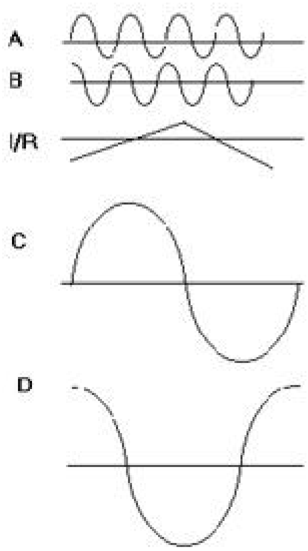
Example

A sine encoder with a resolution of 1024 line per revolution used with an amplifier that has an interpolation factor of 256 (MSININT = 256), provides an encoder output resolution of
1024 * 256 * 4 = 1,048,576. The interpolated output looks like:



Interpolated Output

Commutation Tracks
Sine encoders are available with commutation tracks. Some models come with Hall emulation tracks while others are provided with 2 auxiliary sinusoidal channels called C & D providing absolute positioning within one revolution. The C & D channels are similar to the Sine and Cosine used in resolver feedback devices. The output for sine encoders with C & D channels looks like:



As shown, the A & B channels are interpolated while the C & D channels are used for absolute positioning in one revolution of the motor.

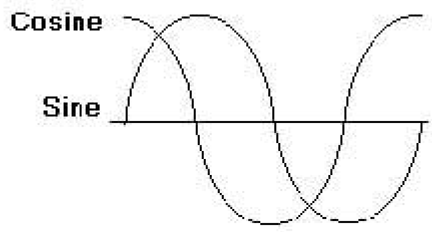
Endat™ Sine Encoders
The Endat Sine Encoder is similar to the sine encoder with C & D channel, in that both are absolute in one revolution. The main difference is in how this information is feed back to the drive for use. The Endat (Encoder Data) sine encoder sends the absolute position back as RS-485 true binary information. The output data is 13 bits, 8192/Revolution. Channels A & B are still open to interpolation by the sine encoder card.

Absolute Multi-turn Sine Encoder
An absolute multi-turn sine encoder utilizes gearing between the shaft and the position wheel. This method provides 4096 coded revolutions. The serial data per revolution is maintained at 13 bits, or 8192 position values per revolution. Channels A & B are still open to interpolation.

Resolvers

A resolver is a rotary transformer whose primary is fed with an AC voltage and has dual secondaries designed to couple the input voltage ratiometrically according to its shaft position. The position feedback signal is provided by the two sinusoidal secondary signals, Sine and Cosine. These secondarys are converted in the drive controller into digital signals by Resolver-to-Digital Converters (R/D or RDC). Resolvers can be single speed or multispeed (referring to the number of electrical cycles per mechanical revolution). Resolvers are durable and tolerate heat very well.

The resolver output signal looks like:



where the Sine and Cosine signal have a 90° phase shift from each other. Converting the resolver signal provides an absolute position signal within one revolution of the motor. The resolution of the converter depends mainly on the motor speed. The chart below shows the R/D converter specifications for a given speed range.

VLIM (RPM)	RDRES	Counts/Rev	Encoder Equiv. Output (C4)
>6100	12	4096	4096 quad counts
1500 - 6100	14	16384	16384 quad counts
<1500	16	65536	65536 quad counts

Resolvers are durable and tolerate heat very well. In addition to the single speed resolver, resolvers can be multi-speed. The counts per revolution increases by a factor of the resolver speed.

Example
A twelve-speed resolver using an RDRES of 12 has 4096 * 12 = 49,152 counts per revolution. The encoder equivalent output is 4096 * 12 = 49,152 quad counts.

One drawback is that the index or reference pulse on the Encoder Equivalent Output is generated at the zero crossovers. On a twelve-speed resolver, there are twelve crossover points. This provides twelve individual indexes pulses out and must be taken into account when homing to the index pulse.

Tachometers

Tachometer - from the Greek Takhos, meaning velocity or speed, and Metron, meaning measurement is a velocity measurement device.

The tachometer - or tach generator - is a voltage generator consisting of a permanent magnet stator and a rotational coil armature whose output voltage is proportional to the rotational velocity of the rotor. This is a true velocity measurement device. Consisting of simple construction and robust materials, typically incorporates silver graphic brushes to increase linearity over the speed range, the device can withstand reasonable shock and temperature exposure. The device is highly linear, very accurate, and has almost no phase lag.

Tachometers are rated to provide a specific voltage per unit of velocity. Some units in which tachometers are rated are:

- V/Rad/Sec Volts per Radian per Second
- V/Krpm Volts per thousand Revolutions Per Minute

Velocity Resolution Issues

Digital drives obtain velocity information from digital information provided by a feedback device. The amount of data the velocity loop gets from the feedback device can greatly affect performance - especially in low-speed and high-gain applications.

- Dither
- Current Noise
- Velocity Ripple

Dither

Dither refers to a very small amount of motion of the motor when commanded to 0 velocity, whether in a velocity loop or a position loop. By the very nature of the digital system, velocity is only recognized when the feedback device changes position enough to signal a change. For instance, a 1024 line encoder results in 1 part in 4096 resolution. This allows a rotary shaft to move over 5 arc-minutes before the feedback device signals a change in position. Effectively, the velocity loop and position loop operate as open loops within this arc. The motor may drift one way causing either loop to eventually detect the velocity and correct it by forcing current to the motor to turn back into the position, but the motor overshoots that position. The velocity (or position) loop detects the incorrect motion in that direction and corrects it by forcing the motion in the opposite direct. This effectively sets up an oscillation around the least significant bit (LSB) of feedback data. Certain conditions set up this condition:

- high loop gains
- high load gains (low inertia)
- lack of dampening (friction)
- coarseness of the feedback data

Therefore, the higher the feedback resolution, the less chance for dither in a given system.

Current Noise

The digital velocity loop performs arithmetic functions on the velocity command and feedback, then generates a current command with the resulting computation. Digital designers are concerned with quantization and truncation errors when designing systems. Quantization errors refer to the data received from the feedback device while truncation errors result from loosing fractional data from the calculations as a result of using finite word lengths. These errors exist as the velocity loop calculates the current command.

In most systems, there is little reason to be concerned about these errors but when high gains are required (large arithmetic multipliers) in the velocity loop. Effectively, the higher the gain, the higher the current commanded from an LSB of the system. In very large gain systems, these resulting errors can cause significant current ripple in the motor resulting in a "white noise" from the motor. The cure for these symptoms is to apply a higher resolution feedback device for the velocity loop, which gives finer resolution to quantization and adjusts the arithmetics to truncate even less fractional data.

Velocity Ripple

The job of the velocity loop is to maintain correct velocity of the feedback sensor. The loop does this by obtaining velocity information from the feedback device. If the velocity feedback device has errors in it, the velocity loop regulates to those errors. This causes the errors to be seen at the motor shaft. The loop has perfect velocity control at the feedback device but the device is not accurate, so the motor shaft shows the error. This effect is referred to as "velocity ripple". In many cases, the motor does not actually respond noticeably to the ripple but the torque transmitted into the load can upset sensitive applications.

Many confuse torque ripple and velocity ripple because the result can be the same. However, the source of the ripple is clearly different.

Accuracy and Resolution

Accuracy is the ability to measure a quantity with a known amount of error. The less error in the feedback device, the more accurate it is.

Resolution is the ability to resolve the measurement to a finite number. The more data that can be obtained from a feedback device, the higher the resolution.

Both accuracy and resolution are important in servo loop control and have different requirements. The paragraphs below discuss why they are important.

- Accuracy
- Resolution
- Repeatability

Accuracy
Accuracy of the feedback device has multiple components. The feedback device manufacturer states an accuracy specification that is generally the most dominant error. Mounting of the feedback device to the motor adds another contribution to error. Analog-to-Digital converters (including Resolver-to-Digital-Converters or RDC) have a specified error. Also, digital systems inherently add 1 LSB of error. A typical resolver system may have the following errors:

10 Arc Minute from Resolver Manufacturer
1 Arc Minute Mounting
8 Arc Minute from RDC
1.3 Arc Minute LSB (14 bit)
Total Error: 20.3 Arc Minute

Resolution
The same 14-bit system has a resolution of 360 degrees / 16,384 or 1.3 Arc minutes - over 15 times more. While it is easy to understand the implications of accuracy, resolution plays an important role. First, the data available within the accuracy at least provides an estimate of position and velocity to the control loops, allowing less truncation and quantitization errors. Secondly, having resolution allows a position loop to position to a finer location that, while is not absolutely accurate, is repeatable and can be compensated for.

Repeatability
Repeatability refers to the ability to repeatedly define the exact feedback position with the exact information. Digital systems are very repeatable, but analog systems inherently have some degree of error caused by hysterisis and gain problems. In general, digital systems are academically considered repeatable to ±1 LSB (least significant bit).