HEWLETT PACKARD

APPLICATION NOTE 1011

Design and Operational Considerations for the HEDS-5000 Incremental Shaft Encoder

INTRODUCTION

A shaft encoder is a component which translates the rotational movement of a shaft into an electrical waveform.

This note is directed to the system designer using the Hewlett-Packard HEDS-5000 modular incremental shaft encoder. The contents are therefore specific and require initial understanding of shaft encoders and their associated systems.

The first section of this note briefly analyzes the theory of design and operation of the HEDS-5000. The second section, covering Design Considerations and Error Analysis, provides an in-depth treatment of the relationship of motor mechanical parameters to encoding error accumulation. Several design examples demonstrate practical utilizations of the techniques presented. The section on Operating Considerations presents information on assembly and test procedures as well as trouble shooting and repair. The last section introduces some circuits and software concepts which will be useful in interfacing the shaft encoder to a digital or a microprocessor based system. A selection guide summarizing the uses and advantages of various encoder characteristics is presented in the Appendix. Also included is a selection of motors suitable for mating with the HEDS-5000 encoder.

DESCRIPTION

A shaft encoder used in a system such as a servo motor control enables the use of digital components in the loop, i.e., a microprocessor instead of servo amplifier, thus lowering the total system cost. A typical digital control loop is shown in Figure 1.

The optical shaft encoder offers several advantages over other encoder types. It is noncontacting, thus it does not burden the system with added inertia and friction, and is inherently more reliable. The encoding speed is high and it offers high noise immunity.

The HEDS-5000 series is a family of modular incremental shaft encoders. Two similar channels whose outputs are in quadrature (90 degrees phase difference) provide velocity and direction information. The output waveform is digital and is compatible with LSTTL logic.

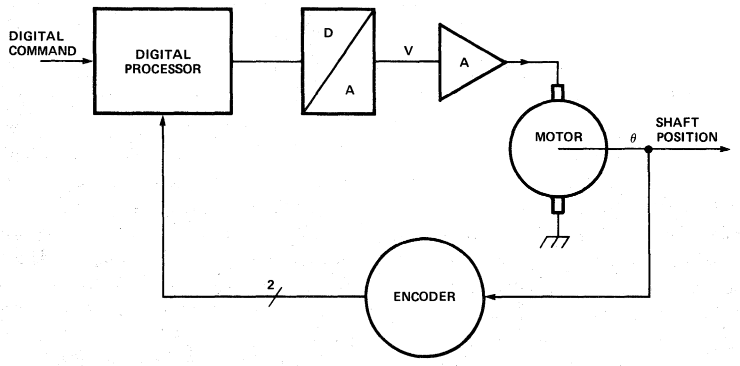

Figure 1. Digital Motor Control Block Diagram

The modular encoder kit is assembled from three parts:

1. The Encoder Body, which contains the phase plate, detectors, and integrated circuits.
2. The Code Wheel, which is mounted on the system's shaft.
3. The Emitter End Plate, containing the light source (LED), which snaps onto the body to form a dust resistant unit.

The assembled encoder is approximately 28 mm in diameter and 18 mm high with a 0.6 metre flat cable providing the electrical connections.

A further physical and parametric description of the product is provided in the HEDS-5000 data sheet.

THEORY OF OPERATION

A light beam interrupted by a rotating code wheel is the essence of an optical shaft encoder. To allow for higher resolution at a given diameter than that achievable by a simple direct beam interruption method, a mask or "Phase Plate" is placed in the light path above the photo detectors. Both the code wheel and the phase plate display a similar pattern of slits and bars, and when viewed together they form what is known as a Moiré pattern. The light from the LED can only reach the detectors when the code wheel slits are aligned with the slits on the phase plate, and since the code wheel is rotating, the detector receives alternating periods of light and dark.

As the resolution of the encoder is increased and the line spacing of the code wheel is decreased, satisfactory operation becomes very sensitive to the collimation of the light transmitted through the code wheel and phase plate, as well as sensitive to the gap spacing between the code wheel and phase plate. To increase the reliability of operation, the HEDS-5000 employs an aspherical lens system and miniature point source emitter which highly collimates the light beam. This highly collimated light allows the code wheel and phase plate separation to be much greater than that achieved in existing discrete component encoders, and also reduces the encoder's sensitivity to shaft axial end play.

Each channel contains two photodetectors with corresponding phase plate patterns spaced in a manner that causes one detector to be dark while the other is fully illuminated. The currents produced by the photodetectors are amplified by a differential amplifier (push-pull). The differential configuration reduces the sensitivity to LED light level changes and thus eliminates the need for any electrical gain adjustments. Digitizing for each channel is accomplished by a comparator which switches when the analog values are equal. The output of the comparator provides LSTTL compatible logic signals.

A block diagram of the HEDS-5000 is presented in Figure 2.

DESIGN CONSIDERATIONS & ERROR ANALYSIS

As in most measurement systems, the encoding process is not error free. It is important to know the causes of errors and understand their effects in order to select a suitable encoder and to define the mechanical requirements of the motor shaft on which the encoder will be mounted.

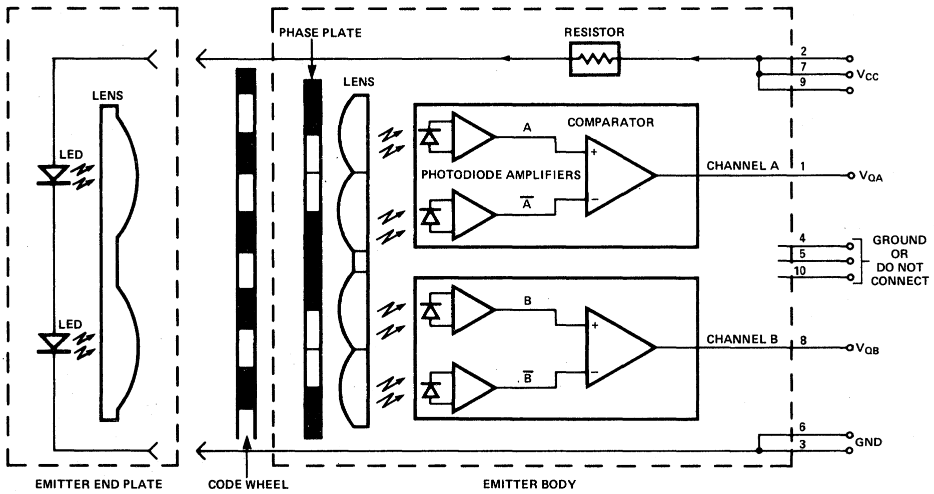

Figure 2. HEDS-5000 Block Diagram

DEFINITIONS

Angular Degree:
The mechanical unit of shaft rotation, i.e., one shaft rotation = 360 degrees.

Code Wheel Count (N):
The number of bar and space pairs around the code wheel, i.e., N=500 in the HEDS-5000 — AXX.

Cycle:
The portion of the output waveform which corresponds to the occurence of a full light and dark period on one detector pair, i.e., there are N cycles in one complete shaft rotation.

Electrical Degree:
The units of the output waveform: 1 cycle = 360 Electrical Degrees = 360/N angular degrees.

Pulse and State Widths:
Portions of the digital output of the 2-channel encoder. See Figure 3 for definitions.

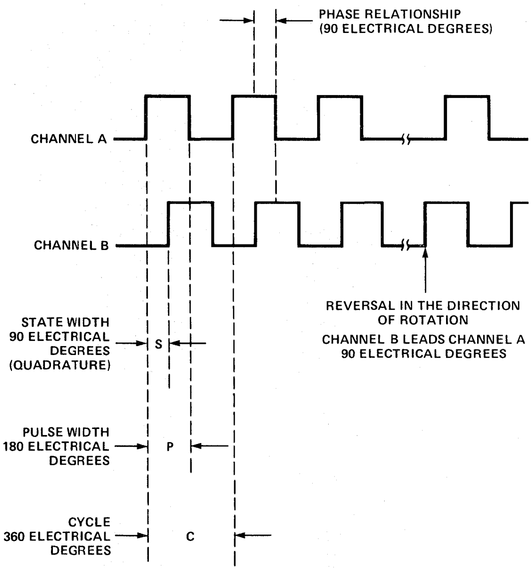

Figure 3. Output Waveform

Phase:
The angle in electrical degrees between the center of the channel A pulse and the center of the corresponding channel B pulse.

Resolution:
The smallest angular motion that can be resolved. Resolution can be expressed as either the number of output transitions in one complete revolution or as the angle of shaft rotation between two consecutive transitions.

ENCODING CHARACTERISTICS

Since there are 500 cycles per each shaft revolution, there are 500 values for each encoding parameter. In the HEDS-5000 data sheet encoding errors are defined in the following manner:

- Typical Error: The average value (over a large batch of encoders) of the maximum error observed in a complete shaft revolution of each encoder.
- Maximum Error: The largest error that should be observed in any batch.

STATISTICAL NATURE OF ERRORS

In a modular encoder, the encoding characteristics of a particular unit cannot be measured directly until the unit is assembled on a system. It would be useful to be able to predict its performance, but, while the errors of any particular unit cannot be predicted with certainty, a statistical treatment will usually result in a good approximation to the behavior of a large batch. The distribution of component characteristics is usually Gaussian and can be described by its mean ($\bar{E}$) and standard deviation (σ). In the case of encoder errors, $\bar{E}$ is defined to be the average of the absolute value of the errors.

When two (or more) factors combine to form a third parameter, their errors can combine vectorially or algebraically. In a vectorial combination, the resultant error could be smaller or larger than the original errors (and sometimes zero). For example, the eccentricity resulting from the random assembly of a code wheel (which has an eccentricity error) and an eccentric shaft is a vectorial combination. An algebraic combination occurs when the two errors always make the resultant error larger as is the case when the pulse width error combines with the phase error to produce state width error.

When estimating the distribution of an error derived from such combinations, the following formulas are used:

1. The new mean is either:
   a. The sum of means in an algebraic combination

$$\bar{E}_T = \bar{E}_1 + \bar{E}_2 + \ldots\ldots \bar{E}_n$$

   b. The root of the sum of squares in a vectorial combination

$$\bar{E}_T = \sqrt{(\bar{E}_1)^2 + (\bar{E}_2)^2 + \ldots\ldots (\bar{E}_n)^2}$$

2. The new standard deviation is derived from the equation:

$$\sigma_T = \sqrt{\sigma_1{}^2 + \sigma_2{}^2 + \ldots\ldots \sigma_n{}^2}$$

DESIGN CONSIDERATIONS

The performance of a modular shaft encoder is affected by assembly and shaft tolerances to a much greater degree than in a pre-assembled encoder with self-contained shaft and bearings. Those factors plus shaft velocity, temperature, and others combine with the intrinsic encoder characteristics to yield the resultant accuracy. A quantitative discussion of the relationship between environmental conditions and accuracy can only be made for a specific encoder type, (i.e., the HEDS-5000), although the general concepts can be extended to others.

Table 1 summarizes the relationships between the encoding parameters and the environmental factors that affect them.

The check mark indicates that the factor listed affects the corresponding encoding characteristics. As can be seen, cycle uniformity is virtually unaffected by factors outside the encoder, while the state width which is the sum of all the encoder transitions will be affected by most of these factors.

Eccentricity and Radial Play

Eccentricity primarily affects position, phase and state width errors. A quantitative discussion of this factor is presented in the specific Encoder Errors section.

The shaft eccentricity which affects the encoder performance is actually a combination of four separate and independent factors:

- Eccentricity: the cyclic off-axis motion of the shaft.
- Radial Play: the random motion due to bearing tolerance and uneven loading.
- Shaft Undersize Tolerance: the cyclic off-axis motion of the code wheel caused by off center mounting of the hub on an undersize shaft.
- Code Wheel/Hub Assembly: the cyclic off-axis motion of the code wheel caused by off center mounting of the code wheel with respect to the hub bore.

Shaft Axial Play

The shaft axial play affects mainly the phase (or quadrature) between the two encoder channels, and to a much lesser degree the pulse width. Aside from phase jitter considerations, the axial play should be restricted to less than 0.5 mm due to the physical constraints of the encoder. The recommended assembly procedure protects the code wheel and phase plate by holding the shaft at its closest point to the phase plate when setting the code wheel. The axial motion is therefore always in the direction of increasing separation, which increases reliability without deteriorating the pulse width performance. When the maximum allowable play is exceeded, the top of the code wheel hub can hit the Emitter End Plate, which is not necessarily catastrophic but certainly undesirable.

Velocity and Temperature

Both position and cycle accuracy are measured between similar transitions of the output waveform and are virtually unaffected by the velocity of rotation. Since counting cycles (by toggling a TTL counter or a similar device) require only a very small time between the logic transitions, the count frequency can typically reach 200 kHz before losing count.

On the other hand, the pulse width is measured between two different transitions and the accuracy will be limited by any difference in the propagation delay of the transitions. This time difference becomes a greater portion of the Pulse Width as the frequency is increased. Propagation delays are also slightly affected by temperature variations.

Assembly

The only adjustment necessary during the assembly of the HEDS-5000 is optimization of the phase between channels. The phase adjustment aligns the axial center of the phase plate pattern to match that of the code wheel. The average phase should be adjusted to 90 degrees. The error in the adjustment process can be limited to about 10 degrees using an oscilloscope presentation of the output. Tighter adjustment tolerances can be achieved by using an averaging phase meter as described in the assembly procedure section.

Table 1

Encoding Characteristic	Factors Outside Encoder Manufacturer's Control				
	Eccentricity	Axial Play	Velocity	Temperature	Assembly
Position Accuracy	X				
Cycle Uniformity	X				
Pulse Width			X	X	
Phase	X	X			X
State Width	X	X	X	X	X

ENCODER ERRORS

Each encoder characteristic contains errors resulting from the relationship between the internal encoder components and the environment. As previously shown, more than one environmental factor affects any encoding error. The discussion below will define these encoder errors, discuss the primary factors contributing to the errors and provide sample calculations as necessary.

Position Error

Position error expressed in minutes of arc or electrical degrees is defined as the difference between the actual shaft position and the position as determined by the output of the shaft encoder. Figure 4 illustrates position error for a code wheel with 8 cycles per revolution.

Position error is primarily caused by off-axis rotation of the code wheel with respect to the phase plate and detectors. The effect of eccentricity is inversely proportioned to the code wheel radius. The position error, $\Delta\theta$, resulting from eccentricity is calculated as follows:

$$\Delta\theta = \frac{kE}{R} \text{ (degrees)}$$

where

$$k = \frac{360}{2\pi}$$

E = eccentricity (mm TIR)

R = code wheel radius

= 10.9 mm for the HEDS-5000

A sensitivity factor Q_p can be defined in order to estimate the contribution of eccentricity to position error.

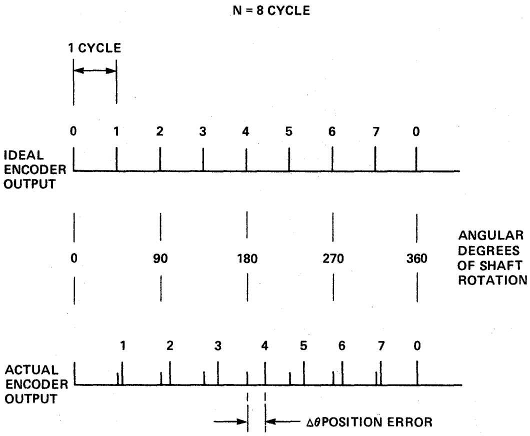

Figure 4. Shaft Encoder Transitions vs. Angle of Rotation

$$Q_p = \frac{k}{R} = 5.3 \text{ angular degrees/mm of eccentricity for the HEDS-5000}$$

Code wheel and phase plate artwork contribute to position error; however, the magnitude is small and can be neglected.

Position error is a concern for high resolution positioning systems. The following example estimates position error of the HEDS-5000 based upon eccentric motion of the code wheel pattern. Such eccentric movement affecting the encoder is actually a combination of the four separate and independent factors discussed earlier.

To Calculate Position Error

1. List the contributing factors. Table 2 presents data which is consistent with the recommended operating conditions as specified in the HEDS-5000 Data Sheet. Code wheel/hub assembly data presented is impirically determined for the HEDS-5000.

Table 2

Contributing Factor	Mean $\bar{E}$	Std Dev. σ
Code Wheel/ Hub Assembly	0.040 mm	0.015 mm
Shaft Eccentricity	0.020 mm	0.005 mm
Shaft Undersize	0.015 mm	0.010 mm

Note that shaft radial play is not included due to the random nature of the contribution. The three factors listed cause predictable cyclic error that are combined vectorially. Radial play contributes to phase and state width error as explained in the following sections.

2. Combine the errors as outlined in the section on the statistical nature of errors to calculate the vector sum of the mean:

$$\bar{E}_T = \sqrt{(\bar{E}_1)^2 + (\bar{E}_2)^2 + (\bar{E}_3)^2}$$

$$= 4.7 \times 10^{-2} \text{ mm}$$

Compute the standard deviation

$$\sigma_T = \sqrt{\sigma_1{}^2 + \sigma_2{}^2 + \sigma_3{}^2}$$

$$= 1.9 \times 10^{-2} \text{ mm}$$

3. To estimate the encoder accuracy it is necessary to multiply by the total eccentricity factor Q_p which denotes the contribution to position error. Recall that

$$Q_p = 5.3 \text{ angular degrees/mm eccentricity}$$

for the HEDS-5000. The average position error, $\Delta\theta$, is:

$$\Delta\overline{\theta} = \overline{E}_T\, Q_r$$

$$= (4.7 \times 10^{-2}\,\text{mm})\ (5.3\ \text{angular degrees/mm})$$

$$= 0.25\ \text{angular degrees}$$

$$= 15\ \text{minutes of arc}$$

The standard deviation $\sigma(\Delta\theta)$ is:

$$\sigma(\Delta\theta) = \sigma_T\, Q_p$$

$$= (1.9 \times 10^{-2}\,\text{mm})\ (5.3\ \text{angular degrees/mm})$$

$$= 0.1\ \text{angular degrees}$$

$$= 6\ \text{minutes of arc}$$

The maximum position error $\Delta\theta_{max}$ is approximately:

$$\Delta\theta_{max} = \Delta\overline{\theta} + 2\ [\sigma(\Delta\theta)]$$

$$= 0.25 + 2\ (0.1)\ \text{angular degrees}$$

$$= 27\ \text{minutes of arc}$$

$$= 225\ \text{electrical degrees}$$

($\overline{x} + 2\sigma$ will contain 98 percent of a normal distribution)

The relationship between shaft eccentricity and position accuracy is illustrated in Figure 5. The residual position error (where shaft eccentricity = 0 in Figure 5) denotes the code wheel/hub assembly contribution to position error. The remainder of the graph includes contribution from both shaft eccentricity and shaft undersize. $E_T + 2\sigma_T$ from our example yields 0.085 mm for maximum eccentricity which corresponds to about 27 minutes of arc on the typical curve. The 99 percentile curve is an indication of the manufacturing process distribution giving rise to the residual position error.

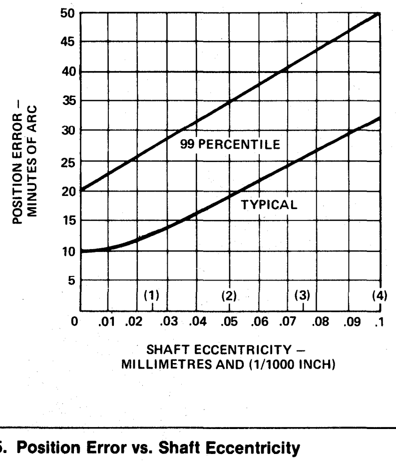

Figure 5. Position Error vs. Shaft Eccentricity

Cycle Error

All cycles will contain 360 electrical degrees; however, the number of mechanical degrees represented by each cycle may vary from the ideal of 360/N. Cycle error, ΔC, is usually expressed in electrical degrees, hence the equivalent angular error:

$$\text{Angular Cycle Error} = \frac{\Delta C}{500}$$

The quality of the code wheel and phase plate artwork is the main factor affecting the cycle error. Data on this parameter is presented in the data sheet. Eccentricity has a minor affect on cycle error and need not be calculated as a significant contribution.

Pulse Width Error

Pulse width error is the maximum deviation of the pulse from the nominal value of 180 electrical degrees.

Although the use of a differential amplification greatly reduces the sensitivity to component and circuit variables, some pulse error will result from a non-uniform light pattern impinging on the differential detectors or an imbalance of the differential elements. An additional error can be observed if, over the temperature range, the encoder is run at high velocities. This is caused by the unequal propagation delays of the falling and rising edges of the digital pulse trains. As with most I.C. parameters, this propagation delay differential is temperature dependent. At 25 degrees centigrade the propagation delays are nearly equal but with increasing or decreasing temperature the delays become unequal. The following equation describes both the frequency and temperature dependence of the pulse width.

$$\Delta P = \propto * \Delta T * f$$

where:

ΔP (Electrical degrees) = Change in pulse width due to operating conditions

ΔT (Degrees Celcius) = $T_{operating} - 25$

f(Hz) = Output Frequency = $\left[\dfrac{\text{Velocity (RPM)}}{60}\right] 500$

$\propto$ = Temperature coefficient (from data sheet)

The typical value for $\propto$ is
1.0×10^{-5} electrical degrees/°C * Hz
but this parameter can reach
a maximum of 2.5×10^{-5} electrical degrees/°C*Hz

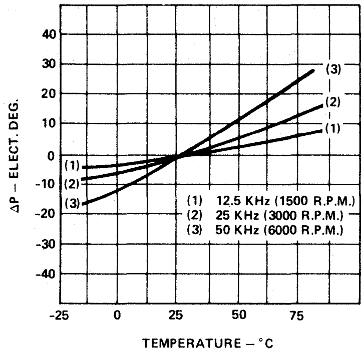

Figure 6. Pulse Width Change (ΔP) vs. Temperature

Figure 6 illustrates the effect of temperature and velocity on the pulse width.

Phase Error

Phase error is the maximum deviation from the nominal value of phase (90 electrical degrees) between channel A and channel B.

Since phase does not extend between two output transitions, strictly speaking it is not an encoding parameter. But since phase error is a direct contributor to State Width Error, it is important to understand the mechanism by which phase error arises.

The average phase of most encoder systems is adjusted during the assembly procedure to be as close as possible to the nominal value of 90 degrees. This helps to average out cyclic variations in phase during a shaft rotation. Therefore the design concern is primarily with respect to the amount that the phase varies as the shaft moves randomly during its rotation.

A shift of the phase between the two encoder channels occurs due to the axial, radial and eccentric movement of the code wheel pattern with respect to the phase plate.

Phase Error Due To Radial Play

The radial play and eccentricity will change the phase in an amount inversely proportional to the square of the code wheel radius.

$$\Delta\phi_R = \frac{K_2\,NE}{R^2}$$

A phase sensitivity factor can be defined in order to estimate the contribution of radial play and eccentricity to phase error.

$$Q_e = \frac{K_2 N}{R^2}$$

= 550 electrical degrees/mm (typical for the HEDS-5000)

The contribution that phase error has on state width error is calculated in the state width error design example and is divided between cyclic eccentricity and random shaft radial play.

Phase Error Due to Axial Movement

Axial movement will also result in a change of phase if the light beams illuminating the two channels are not perfectly parallel. The equation governing phase change due to axial movement is:

$$\Delta\phi_A = \Delta G * Q_{ma}$$

where:

ΔG = change in gap due to axial play (mm)

Q_{ma} = misalignment factor (electrical degree/mm)

A typical value for Q_{ma} as observed in a sample of a HEDS-5000 production run is:

$$Q_{ma} = 20 \text{ degree/mm}$$

Total Phase Error

Phase error contributions due to radial play and axial movement are summed vectorially to give total Phase Error:

$$\Delta\phi_T = \sqrt{\Delta\phi_R^{\,2} + \Delta\phi_A^{\,2}}$$

State Width Error

State Width Error is the maximum deviation of the state width from its nominal value of 90 electrical degrees.

Since the State Width is the combination of all the encoder's transitions, all of the factors which contribute to pulse width and phase error will also contribute to state width error. These error contributions can best be thought of as falling into three categories. The first includes eccentricity contributions resulting in cyclic errors as outlined in the preceding position error section. The second category is factors creating random errors. The third category includes those factors that are due to the intrinsic design of the encoder such as lens quality, I.C. switching characteristics, and I.C. hysteresis. For the HEDS-5000, this collective error is 12 electrical degrees on the average.

A quantitative discussion of the effect that these factors have on state width error is presented in the following design examples.

DESIGN EXAMPLES

In the following examples the state width error of a hypothetical production batch will be estimated. State width is crucial in providing direction information. Thus a minimum state width must be maintained over the whole range of operating conditions. The value of that minimum can range from 1 to 20 electrical degrees or more, and is dependent upon the type of counting circuitry used where directional information must be obtained. Two approaches to the analysis will be discussed. First, state width error at room temperature will be estimated without considering velocity extremes. The second example will answer the question, "What should the test limit at room temperature be to ensure a minimum state width at the extremes of the temperature and velocity ranges?"

Not all of the numbers required in the procedure are available in the data sheet. HEDS-5000 data sheet values are used where possible, and the other encoder values were empirically derived from testing of production assemblies. The numbers relating to shaft variables must be estimated or measured by the designer. The values used below are only for a particular set of motor parameters within the recommended operating conditions of the HEDS-5000. The examples also assume that a phase error adjustment has been made during assembly so that average phase error over 360 mechanical degrees is nearly zero.

Any error in phase results in a corresponding error in state width of equal magnitude. Therefore the sensitivity factors established for phase are used in calculating state width error.

Room Temperature Analysis Example

ECCENTRICITY, ΔS_1

Total code wheel pattern eccentricity was estimated in the position error example.

Mean eccentricity = 4.7×10^{-2} mm

Standard deviation of eccentricity = 1.9×10^{-2} mm

The effect of eccentricity on the state width is obtained by multiplying the total expected eccentricity by the phase sensitivity factor Q_e = 550 electrical degrees/mm.

Since eccentricity is measured as a peak-to-peak value (TIR) and average phase error has been preadjusted to be nearly zero, then the maximum expected movement of the code wheel with respect to the phase plate should be less than or equal to 1/2 the TIR values specified for eccentricity. Hence the mean and standard deviation values for eccentricity used in calculating ΔS_1 are divided by two.

The eccentricity contribution ΔS_1, is:

$$\overline{\Delta S}_1 = \left(\frac{4.7 \times 10^{-2}\,\text{mm}}{2}\right)(550 \text{ electrical degrees/mm})$$

$$= 12.9 \text{ electrical degrees}$$

$$\sigma(\Delta S) = \frac{(1.9 \times 10^{-2}\,\text{mm})}{2}\ (550 \text{ electrical degrees/mm})$$

$$= 5.2 \text{ electrical degrees}$$

RANDOM PHASE, ΔS_2

The contributing factors to random phase should be estimated in conjunction with a Q factor relating to their contribution to state width error. Table 3 summarizes these factors. The shaft axial play and radial play in this example were derived from a typical 31.75 mm (1-1/4 in.) motor with ball bearings. Again, the phase sensitivity factors, Q_e and Q_{ma} which were presented earlier, are used to establish error contribution. The number presented for assembly errors were derived from a typical production run using a phase meter (see "Test Procedures" section) as an adjustment aid.

Table 3

Factor	Units	Mean $\overline{E}$	Std. Dev. σ	Phase Sensitivity Factor, Q
Shaft Axial Play	mm	0.1	0.06	Q_{ma} 20 elect. deg./mm
Shaft Radial Play	mm	0.006	0.003	Q_e 550 elect. deg./mm
Assembly Adjustment	Elect. Deg.	3	3	none

Multiply the mean and standard deviation of each factor by the appropriate Q. Then calculate the total mean contribution by vectorially combining the weighted means. The total standard deviation is obtained by vectorially combining the standard deviation for each factor.

$$\overline{\Delta S}_2 = \sqrt{[(0.1)\ 20]^2 + [(0.006)\ 550]^2 + [3]^2}$$

$$= 4.9 \text{ electrical degrees}$$

$$\sigma(\Delta S_2) = \sqrt{[(0.06)(20)]^2 + [(0.003)(550)]^2 + [3]^2}$$

$$= 3.6 \text{ electrical degrees}$$

INTERNAL ERRORS, ΔS_3

The combination of errors intrinsic to the HEDS-5000 and not directly affected by shaft and assembly tolerances are a result of lens quality, IC switching characteristics and miscellaneous tolerances. These affects summed are approximately the following:

$$\overline{\Delta S}_3 = 12 \text{ electrical degrees}$$

$$\sigma(\Delta S_3) = 6 \text{ electrical degrees}$$

This data was obtained from sample production lots.

Error Distribution

The state width error distribution is computed by algebraically summing* the means of Eccentricity, Random Phase, and Internal Errors. The standard deviations are combined vectorially.

Mean State Width Error $\Delta \overline{S}_T = 12.9 + 4.9 + 12$

$= 30$ electrical degrees

Standard Deviation of State Width Error $\sigma(\Delta S_T) = \sqrt{(5.2)^2 + (3.6)^2 + (6)^2}$

$= 8.7$ Electrical degrees

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*The error contributions are algebraically summed in order to obtain a worst case performance.

The example above predicts the mean state width error for an encoder batch would be 30 electrical degrees when parameters are kept within the recommended operating conditions as specified in the HEDS-5000 data sheet. The state width error for 95% (1.65 σ) of the batch is computed as follows:

$$\Delta S_T = \Delta \overline{S}_T + 1.65 \, [\sigma \, \Delta(S_T)]$$

$$= 30 + (1.65)\,(8.7)$$

$$= 44 \text{ electrical degrees}$$

and is less than 45 electrical degrees. Note: these figures agree with the state width error as specified in the HEDS-5000 data sheet.

Encoders and motors with characteristics resembling the example have been assembled and tested. The resultant state width error histogram is illustrated in Figure 7.

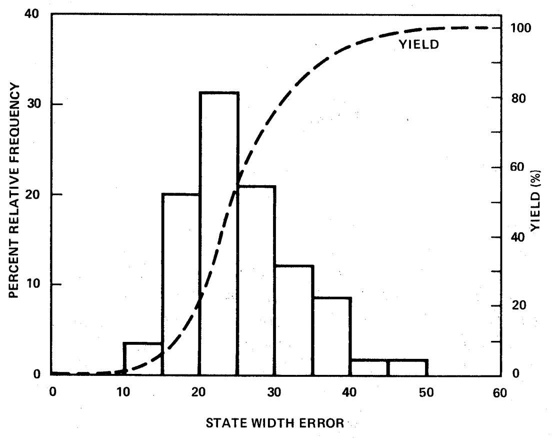


Figure 7. State Width Error Distribution Sample Manufacturing Batch

Designing for Temperature Range

To ensure correct decoding over the full temperature range, the designer might choose one of two approaches:

a. All systems shall be screened over temperature.

b. A guard-banded test limit at room temperature will be chosen to ensure operation over the whole temperature range.

The first approach offers the benefit of higher yields especially when the constraints are tight, but it is cumbersome and often impractical to implement. In the second, the worst case temperature contribution to error is computed and thus the guardband for the room temperature test limit is established.

Below are the steps needed to calculate a room temperature state width error limit that corresponds to an elevated temperature performance specification.

a. Determine the operational requirements — the specifications desired in this example will be to require a minimum state width time of $T_S = 2\mu\text{sec}$ at a temperature up to 60 degrees centigrade with a maximum velocity of rotation of 3000 RPM.

b. Translate the environmental conditions into maximum allowable error — to find the frequency in Hz.

$$f = 3000 \text{ RPM} \left[\frac{500 \left(\frac{\text{cycles}}{\text{revolution}} \right)}{60 \left(\frac{\text{seconds}}{\text{minute}} \right)} \right]$$

$$= 25 \text{ kHz}$$

The minimum state width is then

$$S_{min} = T_s * f * 360$$

$$= (2\,\mu\text{sec})\,(25\text{ KHz}) \left(360 \frac{\text{electrical degrees}}{\text{cycle}} \right)$$

$$= 18 \text{ electrical degrees}$$

or the maximum error is

$$\Delta S_{max} = 90 - S_{min} = 72 \text{ electrical degrees}$$

c. Calculate the temperature dependent error — the formula is:

$$\Delta S = \alpha * \Delta T * f$$

When α is at the worst case value (from data sheet)

$$\alpha = 2.5 \times 10^{-5} \text{ (electrical degree/}^\circ\text{C*Hz)}$$

$$\Delta S = (2.5 \times 10^{-5})\,(70-25)\,(25)$$

$$= 28 \text{ electrical degrees}$$

d. Calculate the room temperature test limit:

$$\Delta S_{max} = 72 \text{ electrical degrees} - 28 \text{ electrical degrees}$$

$$= 44 \text{ electrical degrees}$$

In the previous example, it has been shown that 95% of the units are expected to pass this test limit. If we were to use the first approach, i.e. test all units at 70 degrees centigrade, over 99% of the units are expected to pass the 72 degrees centigrade limit. The reason for the discrepancy is the conservatism of a worst case design.

OPERATING CONSIDERATIONS

Assembly Mounting Surface

The encoder may be mounted directly on a motor which has a two-sided shaft extension or on a remote bearing support at the end of a shaft.

In either case, the mounting surface should be flat and smooth. No special operations are required for the surface finish except removal of burrs that might interfere with the phase adjustment operation which entails sliding the encoder over the mounting surface. The encoder is attached by means of three screws. The mounting surface should therefore be drilled as shown in Figure 8 below and tapped with metric or English threads as required.

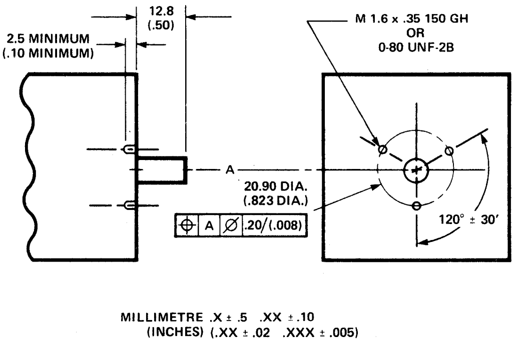


Figure 8. Mounting Requirements

Adhesives

Two different kinds of adhesives are used in the assembly of the encoder.

R.T.V. (silicone rubber) is used on the mounting surface to fill the following functions:

1. Provide a lubricating medium to ease the sliding of the encoder while adjusting phase.
2. Provide a flexible adhesive to accommodate differentials in expansion coefficients between the encoder and its mounting surface.

Dow Corning 3145 (or GE 162) was chosen because in addition to meeting the criteria above, they are non-corrosive and do not emit corrosive vapors.

The Hysol epoxy used in mounting the code wheel onto the shaft was selected to provide a rigid bond when set, and it presents a reasonable compromise between initial viscosity necessary for holding the code wheel in position before setting, setting time, and useful pot life. R.T.V. can be used with success on shaft sizes greater than 1/4 inch. However, the use of R.T.V. on shaft sizes smaller than 1/4 inch is not recommended since the smaller contact area results in a smaller initial holding force and a weaker bond.

ASSEMBLY PROCEDURE

CAUTION: The shaft encoder circuitry may be damaged by an electrostatic discharge. The cable extremities are the susceptible areas. Normal precautions such as ground straps for assembly personnel should eliminate any damage due to electrostatic discharge.

The HEDS-5000 data sheet describes in detail a typical assembly procedure. While the exact procedure in any manufacturing environment might differ due to the variety of applications, it is worthwhile to understand the underlying rationale in the assembly before establishing a specific procedure. There are three steps which may affect the encoder's performance: centering, gap setting and phase adjustment.

Centering the encoder around the shaft using the cone tipped tool (HEDS-891X) provides easier screw insertion and a good starting point for the final phase adjustment.

Although the HEDS-5000 is very tolerant of variations in gap between the code wheel and the fixed phase plate, only a correct initial gap setting will assure full benefits from this feature. It is essential that the code wheel does not touch the phase plate through its rotation, axial movement and vibration. The gap setting tool was designed to eliminate the uncertainties in phase plate height by actually using the plate as a reference for the assembly of each unit. This operation is simple and fast. Assembly of the code wheel at a predetermined height is not recommended since the encoder body worst case tolerances, coupled with the shaft tolerances, could cause the code wheel and phase plate to come into contact. (See the next section for visual inspection procedure of the code wheel/phase plate gap.) Applying R.T.V. on the emitter end plate is recommended as a dust shield but is not required in dust-free environments.

The final step in the assembly is the phase adjustment which can also serve as the final inspection. As mentioned before, in most applications this is a necessary step to provide the required encoding characteristics. Since it is a contributor to state width error, the average phase should be adjusted to a value as close as possible 90 electrical degrees. A plus or minus 10 degree adjustment can be easily achieved using a phase meter as described in the "Test Procedures" section. Adjustment according to an oscilloscope trace of the output is less accurate and demands more training, but the above requirements can be achieved with the proper care and attention.

Where phasing between channels is not of concern (tachometer applications) or if a large initial deviation from proper phasing can be tolerated and corrected, phase adjustment may be modified or omitted.

TEST PROCEDURES

All piece parts of a modular encoder are tested at the factory prior to shipment. Testing the piece parts at the customer's location is difficult since it requires specialized test fixtures. The encoder can best be tested after it is assembled, although some simple tests can be incorporated if an incoming inspection is required.

INCOMING INSPECTION

For Encoder Piece Parts:

Code Wheel: Visually check for shipping damage, i.e., bending or dents which exceed the data sheet limits (code wheel part drawing).

Emitter End Plate: The LEDs can be turned on by passing current through the emitter end plate leads. See Figure 9. The current should be limited to 10 mA and the supply voltage compliance should not exceed 10V for the protection of the LEDs.

Encoder Body: When the 5V supply and ground are connected through the 10 pin connector, the outputs can be observed on a scope. Moving the encoder body in front of an illumination source (e.g., light bulb) will cause the outputs to toggle.

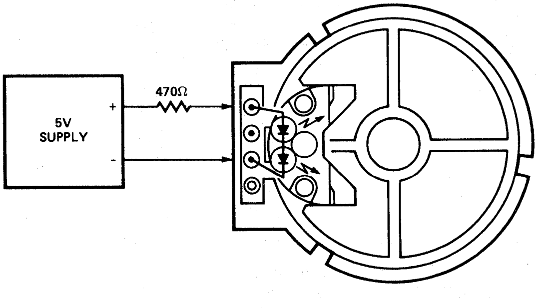


Figure 9. Emitter End Plate Test Configuration

For Motors:

Shaft: For shaft tolerance definitions and testing see Appendix C.

Assembly: The gap at which the code wheel was set cannot be measured directly but with some practice a visual estimate can be made by observing, with proper magnification, the parallax between the code wheel slits and the phase plate pattern.

Phase Adjustment/Final Test: The final step in assembly is the phase adjustment. It can be achieved using a scope or an averaging phase meter. The set up and waveform for the scope test are presented in Figure 10. When setting the phase, it is advisable to turn the shaft in both directions and adjust for minimum phase error.

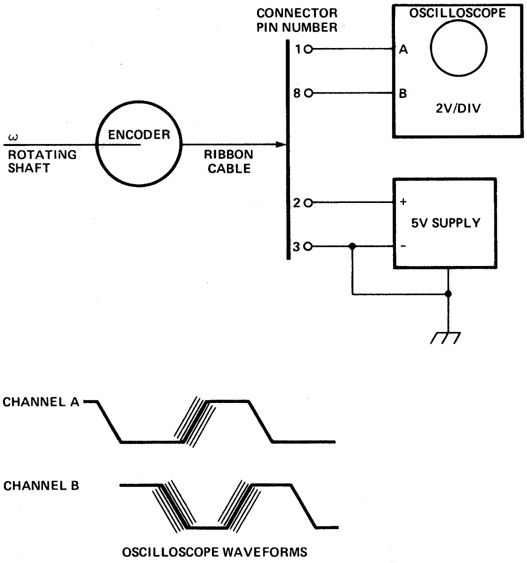


Figure 10. Scope Test Set-Up

Figure 11 is a schematic for an averaging phase meter which makes the task of adjusting the phase between channels easier and more accurate.

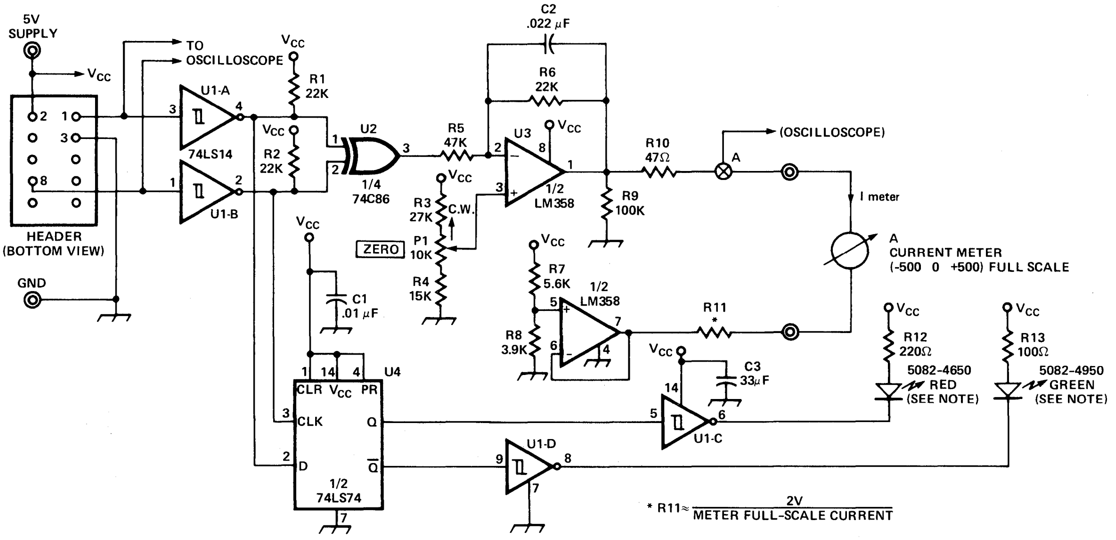
Operating Instructions:

1. Observe the LEDs on the phase meter to verify that the shaft rotation and LED director indication correspond.
2. Recheck shaft direction or adjust the phase until correct.
3. Adjust the encoder (see assembly instructions in data sheet) for zero reading on the phase meter.

Note: Occasionally due to statistical variations in the pieceparts, a high pulse width or phase error may be observed and can be improved by replacing the emitter end plate with another. The original end plate can subsequently be used on another unit, usually without causing the problematic symptoms.

TROUBLE SHOOTING AND REPAIR

The HEDS-5000 does not require any adjustments after it is assembled, thus minimizing the need for field service. The emitter end plate can be removed, but care must be exercised to prevent bending the wire leads on the encoder body. Pry slots are provided on the end plate circumference for easy opening. When the end plate is removed, a light source can be directed towards the encoder body and the shaft rotated to observe the change of state in the output channels. If the encoder body checks OK, and the wire leads are inspected, a new end plate can be snapped into place and the encoder retested. The removed end plate can then be inspected as described in incoming inspection procedures.



* R11 ≈ $\frac{2V}{\text{METER FULL-SCALE CURRENT}}$

NOTE: THE RED L.E.D. IS LIT WHEN CHANNEL A (PIN 1) IS THE LEADING WAVEFORM.

Figure 11. Phase Meter Circuit

OPERATING ENVIRONMENT

Certain operating environments could have an adverse affect on the materials used in the manufacture of the HEDS-5000. To allow the user to evaluate these situations, the following information on the generic material constituents of the encoder is supplied.

Piece Part	Material
Encoder Body & End Plate	Glass Filled Nylon
Emitter & Detector Lenses	Polycarbonate
Cable Jacket	Polyvinylchloride
Code Wheel	Nickel Alloy

INTERFACE

For the encoder to serve as a useful function in a system, it must be interfaced correctly both mechanically and electrically.

HARDWARE

The flat ribbon cable supplied with the encoder is a cost effective cable for most applications. An unshielded cable can sustain relatively high levels of electromagnetic interference without affecting the encoder's performance. On the other hand, this cable is constructed of solid copper wire which is not designed for repeated flexing or relative motion between the encoder body and connector. Figure 12 illustrates the location of stress concentration during flexture. To avoid stress concentrations during relative movement or in a high vibration environment, it is recommended that the cable be tied down as shown in Figure 13. The remainder of the cable should be mounted to minimize repeated flexture in any specific area. Consult the factory for further information involving relative movement of the encoder.

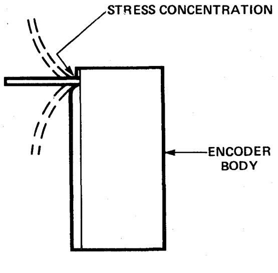


Figure 12.

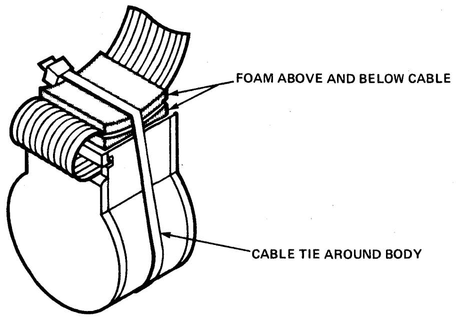


Figure 13.

The standard HEDS-5000 is supplied with a 10-pin female insulation displacement type connector mounted on the ribbon cable. Table 4 lists a few of the available mating connectors which may be utilized to interconnect the encoder to external circuitry.

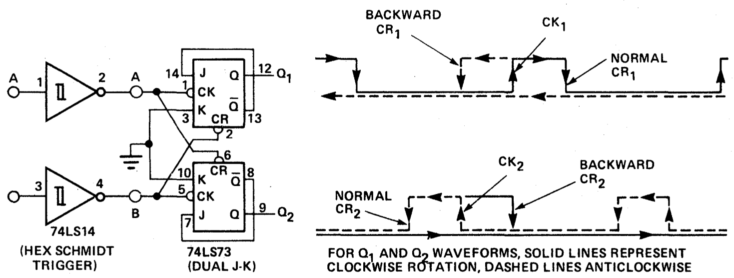
Table 4

Manufacturer	Part Number
AMP	102154-1 102160-1
Molex	10-56-2101 10-55-2101
3M	3446-2002 3446-1002
Berg	65962-001
Robinson-Nugent	IDH-10-S1 IDH-10-SR1

CIRCUITS

Although some applications require the use of only one channel, i.e., tachometers or a unidirectional shaft rotation, the most common application will involve the integration (count) of the shaft position, and thus require the information from both channels to determine the direction of rotation. The basic circuit counts cycles, while a slightly more complex version which counts both transitions of a channel (2x) is sometimes useful. In all cases it is recommended that the digital output of the encoder be buffered by an LSTTL Schmitt trigger (74LS14). The use of a Schmitt trigger gate increases the fan out capabilities while lowering the system's susceptibility to errors caused by slow transition times of the encoder's output.

The circuit depicted in Figure 14 provides an up or down pulse for every cycle. Due to the latched hysteresis configuration, the circuit avoids the multiple count problem which can occur in the event of a stationary shaft oscillating slightly about a transition.



BASIC DIRECTIONAL SENSING. FOR CLOCKWISE ROTATION, Q_1 PULSATES; FOR ANTICLOCKWISE ROTATION, Q_2 PULSATES.

Figure 14. Cycle Count (1X) Circuit

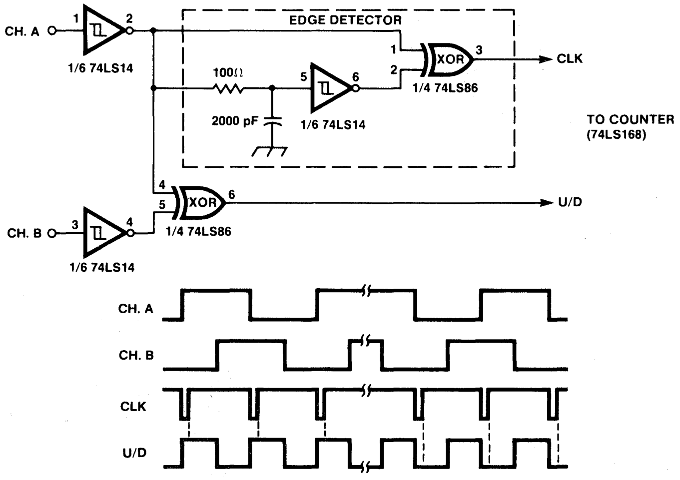


Figure 15. 2X Count Circuit

By counting each transition of an output channel, the resolution can be increased to enable the distinction between the high and low states of the channel. The edge detection circuit shown in Figure 15 provides a pulse for each transition of channel A. The Exclusive OR gate toggles at twice the channel frequency of each channel, but when observed coincident with the negative slope of the edge detector output, its state corresponds to the direction of rotation. These two outputs can be used to drive the clock and control inputs of an Up/Down counter such as the 74LS168.

MICROPROCESSOR INTERFACE

The approach used for interfacing to a microprocessor could vary depending on the design requirements. An interrupt driver routine is simple to implement and is suitable for lower speeds. Using a programmed input routine can lead to a minimum hardware design and can accommodate higher rotational velocities. For very high velocities the encoder output can be buffered to a hardware counter before being input to the microprocessor.

Interrupt Driver Design

```
Interrupt Routine:
  Input channel A & B into Accumulator.
  Mask all but bits 0 & 1.
  IF Accumulator = 1 or 2.
  THEN
    Increment count register.
  ELSE
    Decrement count register.
```

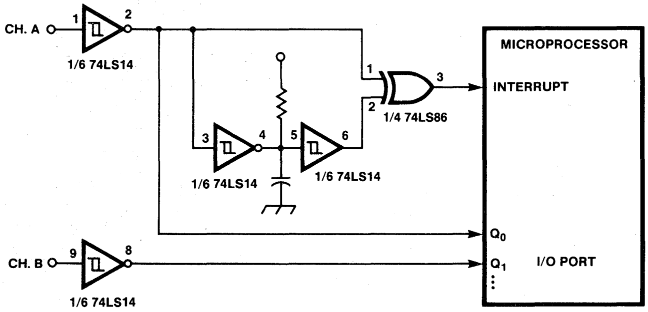


Figure 16. Interrupt Interface

Utilization of the overflow flag enables the designer to increase the effective counter width to fill his maximum count requirement.

Programmed Input: The sampling of the decoder outputs and the decode algorithm are written as an integral part of the program flow thus eliminating the time overhead associated with interrupt routines. Since the sampling is now independent of the encoder transitions, the shaft velocity must be limited, to enable the processor to sample the encoder at least once per output logic state.

The maximum velocity can be computed as follows:

1. The minimum state width is required to be longer than the program cycle.

$$T_s \left(1 - \frac{\Delta S_{max}}{90}\right) > T_p$$

where:

T_s = Nominal state width time at maximum frequency

T_p = Program Sampling Period

ΔS_{max} = Maximum State Width error

2. Substituting T_S from above, the maximum frequency is:

$$f_{max} = \frac{1}{4T_S} = \left(\frac{1 - \frac{\Delta S_{max}}{90}}{4T_p}\right) \text{ Hz}$$

ΔS maximum is estimated using the methods outlined in the "Design Considerations" section. Since ΔS is also a function of frequency, a first guess at the frequency should be assumed and a second iteration might be required (for very fast program cycles) to converge the result and the assumption.

The maximum allowed velocity is derived from f_{max}:

$$\omega_{max} = (2\pi f_{max}/N) \text{ rad/sec}$$

where:

N = Code Wheel count

Example: A motor which is required to run at speeds up to 600 R.P.M.: The estimated state width error is 45 electrical degrees. Compute the maximum sampling period.

$$f = \left(\frac{600}{60}\right) 500 = 5 \text{ KHz}$$

$$T_S = \frac{1}{4f}$$

$$= 0.05 \text{ msec}$$

$$T_p \leqslant T_S \left(1 - \frac{\Delta S_{max}}{90}\right)$$

$$\leqslant 0.05 \left(1 - \frac{45}{90}\right) \text{ msec}$$

$$\leqslant 25\ \mu\text{sec}$$

The maximum allowable time between input samples is 25 μsec. The total program cycle should not exceed that number if none of the encoder's counts are to be missed.

DECODE ROUTINE

A programmed decode routine should have the previous state stored in memory. After the present state is input, a decision can be made on the direction of rotation (if any). This can be handled by accessing a look up table at a location determined by the two bit word representing the previous state, and whose content is the expected word for the next state in a clockwise rotation.

BUFFERED DESIGN

The level of buffering will depend upon the ratio of the encoder's frequency and the microprocessor sampling frequency.

The single stage memory element (Flip-Flop) described in Figure 15 will increase the maximum allowable encoder frequency by a factor of approximately 2.5 and still enable the counting of 2 transitions per cycle.

To achieve higher shaft velocities, the encoder can be buffered by an up/down counter. The parallel counter word is accessed by the microprocessor.

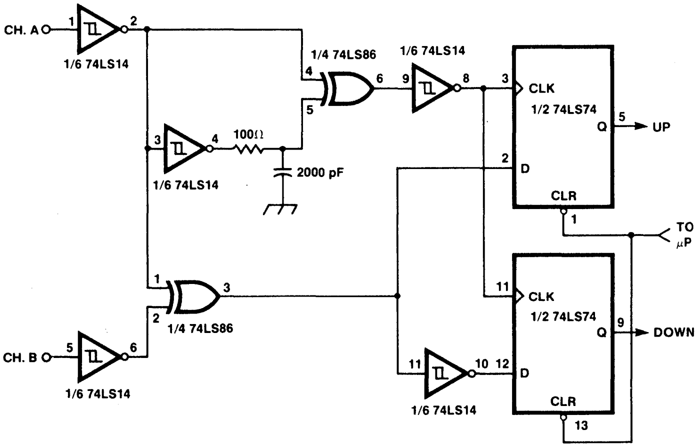


Figure 17. 2X Up/Down Buffer

SHAFT POSITION COUNTER

An optical incremental shaft encoder is a cost effective, reliable component for measuring shaft position. Since its output is a pulse for every increment of rotation, external circuitry is required to integrate the pulse train and indicate the shaft's position.

The circuitry presented in Figure 17 translates the encoder's output into the inputs required by an Up/Down counter. The count resolution is two times the code wheel count.

APPENDIX A
ENCODER SELECTION

PARAMETER	DESCRIPTION	MAIN ADVANTAGES
TYPE:		
ABSOLUTE	Provides a binary "word" for each position. Each bit requires a separate optical channel. The resolution is equal to the number of output bits.	Constantly retains the correct position information for one revolution. Not affected by power shut-off.
INCREMENTAL	Provides a pulse for each increment of shaft movement. Usually consists of two optical channels to enable the determination of the direction of rotation.	Lower cost than absolute due to the limited number of channels. Higher reliability. Encoded position not limited to one revolution.

PARAMETER	DESCRIPTION	MAIN ADVANTAGES
NO. OF CHANNELS:		
1 CHANNEL	Only one pulse train.	All the information required for unidirectional applications.
	Timing is proportional to speed.	Least expensive electronics.
2 CHANNEL	Two output waveforms in quadrature.	Provides information on direction of rotation. Can be integrated to obtain position.
3 CHANNEL	As in two channel, plus an output providing a single pulse per revolution.	Provides an absolute indication of shaft position once per revolution. Can be used to reset position counters.
CONSTRUCTION:		
SELF-CONTAINED	The encoder is supplied as a functional unit containing its own bearings and shaft.	Easy to use. Less assembly and testing required. Less affected by shaft eccentricity and loading.
MODULAR	The encoder is supplied in kit form and assembled by the user on the system's shaft.	Lower cost. Smaller size. Less inertia and friction due to the elimination of the internal bearing. Does not require alignment of two shafts. Does not add torsional resonance between encoder and motor due to long shaft.
ENCODING:		
DIRECT	A slotted wheel interrupts the light path between a light source and a photo-detector. The spokes and slots on the wheel are as wide as the light beam, thus limiting the maximum resolution.	Simple. Low cost.
MOIRÉ	A mask of a bar/slot pattern is placed on the photodetector. A code wheel which has a similar pattern is rotated in the light path. The light reaches the detector only when the slots on the code wheel and the mask line up. The resolution is therefore limited only by the slot spacing on the mask and code wheel and not by the light beam diameter.	High resolution can be achieved without sacrificing detector size.

PARAMETER	DESCRIPTION	MAIN ADVANTAGES
OPTICS:		
NOT LENSED	The light beam is allowed to diverge from the source. In this configuration the separation (gap) between the code wheel and the masked detector has to be very small in order to maintain sufficient light modulation on the detector.	Low cost, suitable for lower resolution encoder.
FOCUSED	A lens focuses the emitted light on the code wheel. Any shaft play will move the code wheel from the optimal position increasing the beam size and thus reducing the modulation contrast.	Efficient light collection. Allows higher resolution than the non lensed design — when not using the Moiré encoding method.
COLLIMATED	A lens collects the light from a small source and transforms it into a parallel pencil of light directed towards the code wheel and the masked detector. The light modulation is not sensitive to the code wheel-mask separation, allowing wider gap at higher resolution.	Wider gap. Allows looser shaft play specifications. Allows higher resolution. Efficient light collection.
LIGHT SOURCE:		
INCANDESCENT	A small light blub.	High output power.
SOLID STATE	A light emitting diode provides red or near infra-red light.	Lower current consumption. Better reliability. Smaller, more consistent source enables better collimation.
CODE WHEEL:		
GLASS	The bar pattern is printed on a glass wheel.	More resolution capability. Better cycle accuracy. Flat.
METAL	The pattern is composed of slots in a metallic disc.	Lower inertia. Higher Resolution/Inertia ratio. Pattern is scratch resistant. Rugged.

PARAMETER	DESCRIPTION	MAIN ADVANTAGES
SIGNAL CONDITIONING:		
SINGLE ENDED	A single detector per channel collects the modulated light. The resultant photo current is amplified by a single ended amplifier. Digitization is accomplished by comparing the amplifier output to a reference level (usually at half the peak value). Any change in the light path, i.e., source degradation, will affect the symmetry of the digitized waveform.	Low cost.
DIFFERENTIAL (PUSH-PULL)	The mask pattern of two adjacent detectors is spaced so that a light period on one corresponds to a dark period on the other detector. The resultant currents are amplified by a differential amplifier. Digitization is accomplished by comparing the outputs to each other.	Stable waveform. Less affected by time, temperature, or alignment changes.
OUTPUT:		
ANALOG	The amplified triangular waveform is output to be digitized by external circuitry.	The output can be used for interpolated analog position feedback. Sometimes used also in velocity feedback.
DIGITAL	The digitization occurs within the encoder.	Interfaces directly to digital circuitry. Higher noise immunity. Simpler interconnect cable requirements.

APPENDIX B
SUITABLE DC MOTORS

The use of encoded motors in position control applications often requires that the motor be specially fabricated to meet particular requirements with respect to torque, speed, diameter, shafts, housings, etc. It is not, therefore, practical to list to any significant extent all of the motors which may be utilized in conjunction with the HEDS-5000.

There are four mechanical motor shaft parameters which must be held within specified limits in order for the encoder to operate properly. These parameters are:

Axial End Play
Shaft Perpendicularity
Shaft Eccentricity (run out)
Radial Play

Absolute maximum values for these parameters, along with recommended operating conditions, are specified in the HEDS-5000 data sheet.

As a resource for those who wish to obtain motors for evaluation of the HEDS-5000 performance, the products as listed in Table 5 have been evaluated and samples have been found to meet the required data sheet specifications. There are many other manufacturers of motors suitable for use with the HEDS-5000, as well as other motors from the listed manufacturers which are equally suitable.

Table 5

Manufacturer	Family
Electro Craft	508,510 Series
Pittman	8000, 9000 & 13000 Series
Portescap	23021, 26PC11, 28PL21, 34L11 Series
Transicoil	All motors which have 5/32" & 1/4" shafts

In reviewing motor data sheets, it will be found that size is well specified; however, motor vendors rarely specify the previously mentioned mechanical parameters in their data sheets. Dialog with the manufacturer will be necessary in order to obtain data on motor shaft parameters.

Some suppliers offer sleeve bearings or pre-loaded ball bearings for securing the shaft. Pre-loaded ball bearings improve the shaft parameter values and may be required in order to achieve the desired specifications.

The encoder mounting requirements must be communicated to the motor vendor to ensure correct alignment of the encoder. This may require that an additional mounting plate with screw holes be machined for the motor.

Testing for axial end play, shaft perpendicularity, shaft eccentricity, and radial play is necessary to determine acceptance of motors to incoming inspection criteria. The user should be sure that the test conditions represent the requirements of the HEDS-5000 encoder. For example the code wheel is placed approximately 10 mm from the mounting surface when the encoder is assembled. Therefore perpendicularity, eccentricity, and radial play measurements should be made 10 mm from the mounting surface.

APPENDIX C
MOTOR SHAFT PARAMETERS