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1. INTRODUCTION

The use of motion transducers has become commonplace and increasingly important to motion control systems designers in all sectors of manufacturing industries. As rapid advances in size, accuracy, resolution, and application sensitive mechanical packaging develops, close loop systems become more attractive to design engineers. The broad range of devices that are currently available can offer design engineers multiple solutions to their motion control needs.

This handbook intends to provide a clear understanding of the fundamental principles involved in the operation and application of various types of motion transducers. Primarily, this book will be concerned with incremental optical encoders, both linear and rotary.

This handbook has three broad objectives:

1. To provide a framework for identifying the proper motion transducer to use in a given application.
2. To provide a basic understanding of encoder operation.
3. To guide the users through the major steps of interfacing an encoder with their system.

Sections 2, 3, and 4 address the first two objectives. The major types of motion transducers and their relative advantages are described in Section 2. In Section 3, major types of encoders are described. Operation of Dynamics Research Corporation's optical incremental encoders is discussed in Section 4.

Encoder interfacing considerations are discussed in Section 5, as well as determinants of encoder life and total system error.

The encoder applications described in Section 6 were selected to illustrate the principles discussed in preceding sections. Also, they indicate the broad utilization of encoders in various manufacturing applications, for both end users and OEM's.

2. MONITORING ROTARY AND LINEAR MOTION

Measurement and control often involve monitoring rotary and linear motion. Measurement and control are multi-stage processes with the first stage of either process, the generation of an electrical signal, to represent the motion. When measurement is the objective, this signal is used to quantify the desired property (i.e., displacement, velocity, etc.), and the data are translated to a format that can be understood by the end user. When control is the objective, the signal is used directly by the associated controller.

Whether measurement or control is required, generation of the electrical signal to represent the motion is accomplished with transducers. The design and selection of a transducer is determined through the evaluation of application considerations. An overview of these parameters is presented in this section.

TYPES OF TRANSDUCERS

Major types of transducers used to monitor motion are

- Proximity Switches
- Potentiometers
- Analog Inductive Components
- Encoders

The transducer that should be used in a given application depends on the performance requirements, environmental constraints, and other factors such as cost, space requirements, etc. Some of the more important design considerations are listed in Table 2-1. The following is a description of each transducer type with their relative strengths and weaknesses.

Table 2-1. Design Considerations

<p>I. APPLICATION</p> <ul style="list-style-type: none"> A. Measurement or Control or Both B. Analog or Digital Output Required C. Response Characteristics D. Type of Measurement <ul style="list-style-type: none"> 1. Displacement 2. Velocity 3. Acceleration 4. Force, Pressure, or other Quantifiable Variables E. Interfacing Requirements <p>II. PERFORMANCE</p> <ul style="list-style-type: none"> A. Accuracy B. Resolution C. Speed, Acceleration, and Friction Force D. Reliability E. Life 	<p>III. ENVIRONMENTAL CONSTRAINTS</p> <ul style="list-style-type: none"> A. Temperature B. Air Pressure and Humidity C. Mechanical Shock and Vibration D. Electrical Noise E. Foreign Matter (Grease, Dirt, Water, etc.) F. Magnetic Fields G. Nuclear Radiation <p>IV. OTHER</p> <ul style="list-style-type: none"> A. Cost B. Installation and Assembly Requirements C. Maintainability D. Size E. Weight
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PROXIMITY SWITCHES

Proximity switches, probably the oldest of the control elements, are basically location sensing devices. They include true mechanical switches, photo sensors, magnetic pickups, pressure sensors, etc.

Proximity switches have historically been the primary location indicating device in control systems, but rarely used for measurement except in “go-no-go” gauging. Output is a discrete change in signal level, and these devices are easily interfaced with both custom controllers and computers. Response of me-

chanical switches is relatively slow. Precautions must be taken to ignore the multiple signals generated by contact bounce when these switches are monitored with control devices such as computers that are capable of rapid response.

POTENTIOMETERS (ROTARY AND LINEAR)

Potentiometer outputs, from both rotary and linear devices, depend on the position of a sliding contact on a resistive element, as illustrated in Figure 2-1. Normally operated as a voltage divider, output is analog, and analog to digital hardware is required for digital output applications. Potentiometers are often used to measure displacement as opposed to proximity switches whose chief function is control safety or limiting. Potentiometers are moderately accurate devices when properly calibrated, but are susceptible to degradation due to wear. Resolution may be limited, but is often adequate for many applications. Potentiometers are susceptible to many environmental constraints. Essentially mechanical contact devices, they must be protected from shock, vibration, and foreign matter contamination.

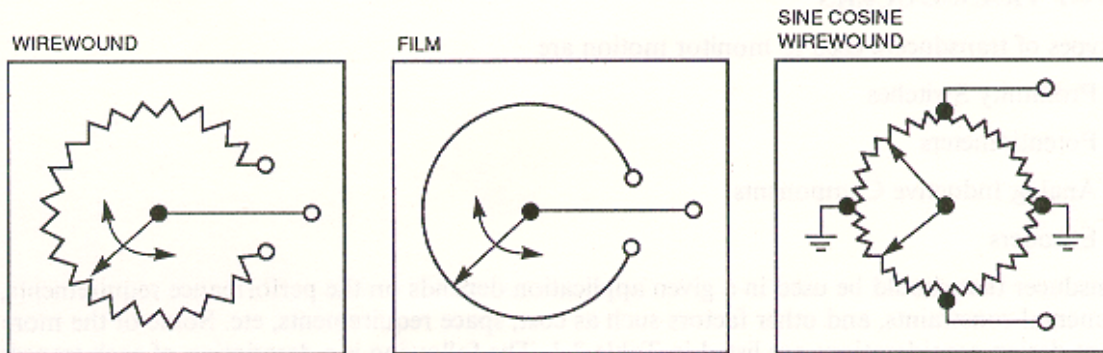


Figure 2-1. Potentiometers

ANALOG INDUCTIVE COMPONENTS

Inductive transducers are widely used devices for both rotary and linear applications. Similar to the transformer, alternating current in one coil (primary) induces alternating current in an adjacent coil (secondary), the principle of operation is electromagnetic coupling between parallel conductors. Position can be deduced accurately with external electronics and output is sinusoidal.

There are many variations of inductive transducers. Some of the most common are synchros, resolvers, induction potentiometers, and linear variable differential transformers (LVDTs).

A true synchro resembles a three-phase motor, but produces an electrical output corresponding to the angular position of its shaft. The output is analog and its position can be interpreted from the relative voltage, amplitude or phase. The synchros can be connected so that the output shaft assumes the same relative position as the input shaft, as shown in Figure 2-2.

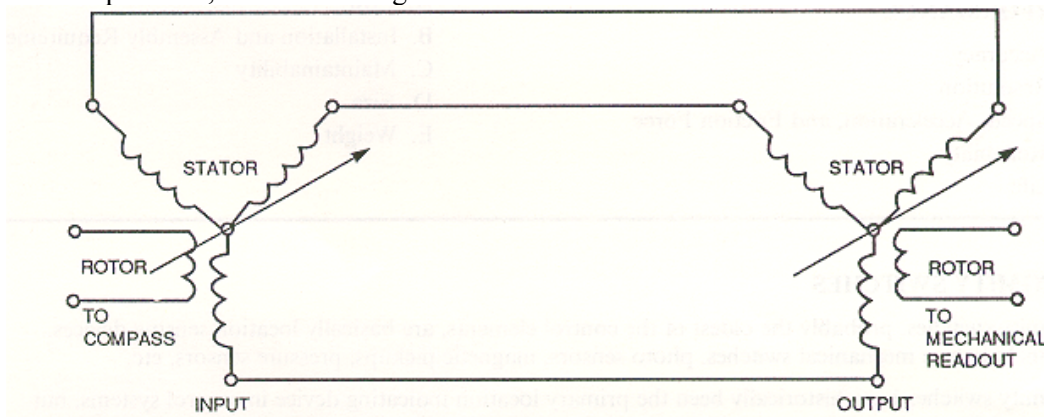


Figure 2-2. Direct Mechanical Readout with the Synchro

Resolvers are similar to synchros except they have two stator coils at right angles rather than three separated by 120° . The most simple resolver, the four-pole, is illustrated in Figure 2-3. The outputs V_1 , and V_2 depend on the angles between the rotor and the stator coils. Higher resolution resolvers are produced with additional pairs of coils.

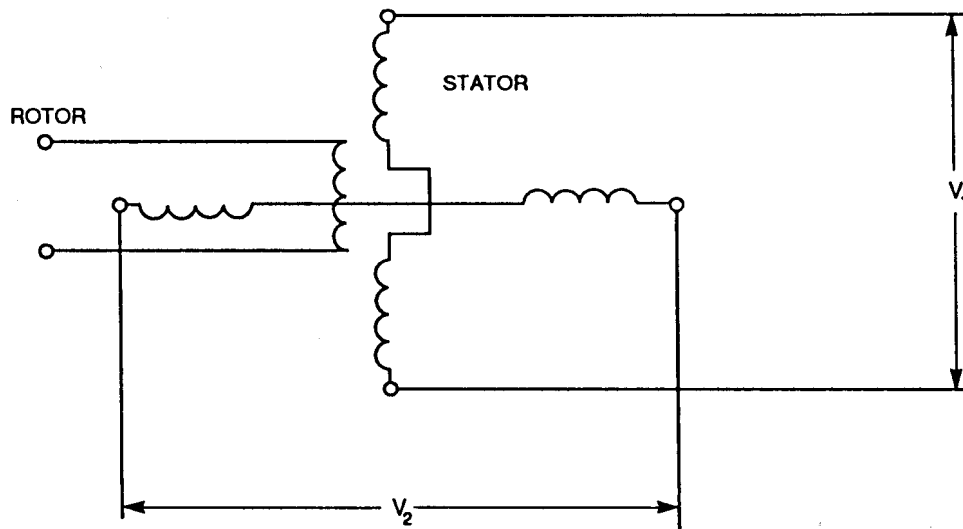


Figure 2-3. Four Pole Resolver

ENCODERS

Encoders can be categorized into two broad types: contacting and non-contacting. The contacting type requires brushes or finger sensors that electrically transmit a signal to indicate a change in position. Non-contacting encoders rely on magnetic, capacitive or optical phenomena to sense the motion. Outputs can be either absolute, a digital coded word that indicates absolute position, or incremental, with repetitive pulses that are counted to accumulate total motion.

Rotary position sensing, either absolute or incremental, indicate the rotation of a shaft. The encoding disc is patterned with radial lines that are sensed as the input shaft is rotated. Mechanical packaging varies greatly depending on application requirements.

Linear position sensing depends upon a moving head whose motion is sensed along a linear track and a scale. Principles of operation and output types are similar for rotary devices. Mechanical packaging accommodates a wide spectrum of application requirements.

OPERATIONAL CHARACTERISTICS OF THE TRANSDUCER TYPES

Potentiometers, encoders, and inductive transducers are used for both measurement and control. The wide variety of these devices creates a considerable overlap in their application. The proximity switch is technically a measurement and control device but because of its limited two-stage output, it is not normally performance competitive with other devices.

For comparison, Figures 2-4, 2-5, and 2-6 illustrate the components required to measure rotary displacement with the encoder, resolver, and potentiometer. The gear train is normally required in resolver applications to achieve the desired resolution. A/D conversion is required for both the resolver and potentiometer applications. However, resolver A/D is considerably more complex than that for the potentiometer because of the switching logic required to follow the resolvers multiple output.

Deciding which transducer type will yield optimal performance in a particular application will require evaluation of operating conditions regarding accuracy, resolution, speed, acceleration, force, reliability, and life expectancy of the component.

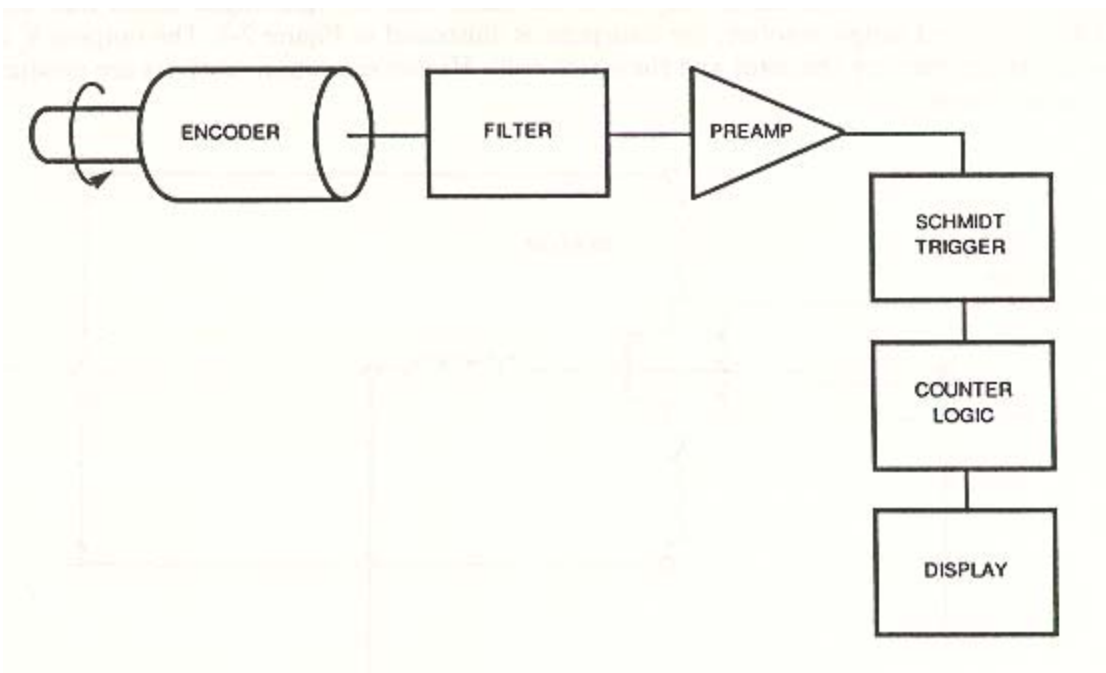


Figure 2-4. Measurement and Display of Rotary Displacement Using the Encoder

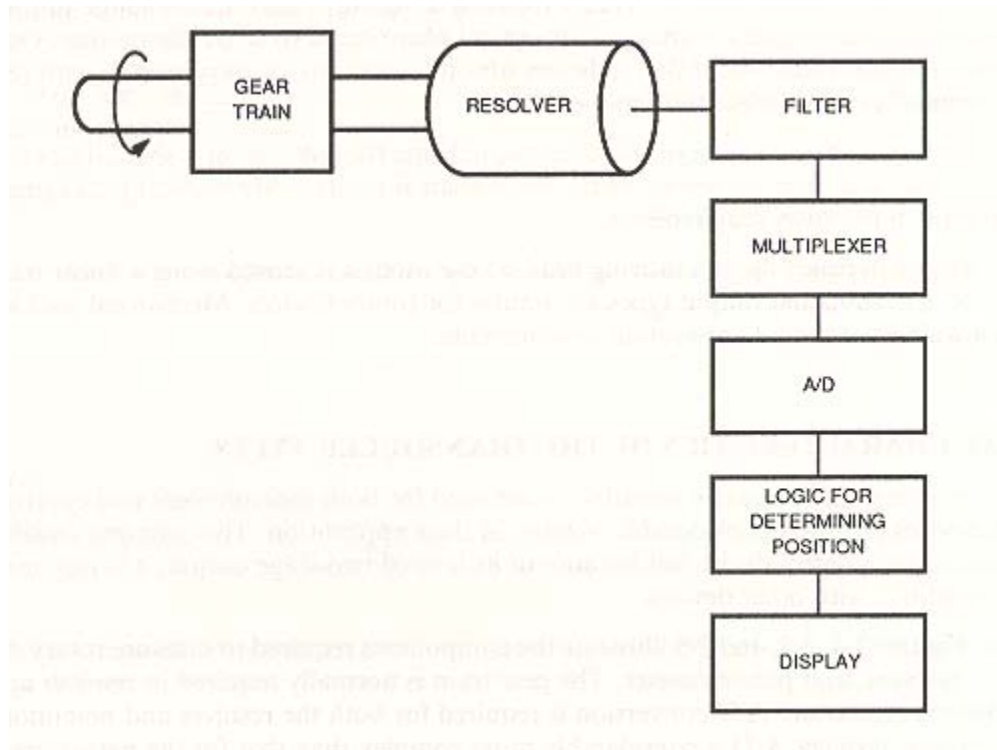


Figure 2-5. Measurement and Display of Rotary Displacement Using the Resolver



Figure 2-6. Measurement and Display of Rotary Displacement Using the Potentiometer

Accuracy, defined as the difference between the actual position and the ideal position, is typically quantified by summing all error generating components of a particular device then comparing the average results to an accepted reference or value. The degree of precision of a particular transducer type varies. Each types inherent ability to accurately report the smallest amount of motion changes considerably and should be identified as an important distinction when evaluating accuracy.

Resolution is often confused with accuracy. Resolution is strictly a particular devices ability to divide angular or linear displacements into so many divisions over a particular distance. Typically, angular divisions are reported in degrees, minutes, and seconds of 360° . Linear displacements are reported in divisions per inch or millimeter. Typically, potentiometers and proximity switches are considered low resolution, while inductive devices and encoders range from low to high resolution.

Other properties which must be considered when choosing the appropriate device include maximum speed, acceleration, and starting force.

The speed at which a transducer type can be operated will be constrained by both mechanical and electrical factors. Mechanically, components of a transducers design which frequently limit speed are contacting components such as brushes and ball bearing assemblies. Electrically, limitations result because some types of electrical components are limited in their ability to respond or transmit quickly enough to track motion accurately. Maximum operating speeds are specified based on these limiting factors with life expectancies of a particular device considered. Typically, it is mechanical factors which limit life expectancy.

Acceleration is a component of speed. Restricted electrically by the same electrical conditions, it must mechanically overcome inertia as well as structural limitations inherent in a design to ensure survival over the specified life.

Reliability and life of a transducer are functions of the integrity of the design and the effects of the application on the device under normal operating conditions. As with all the above characteristics, each transducer type has a wide range of capabilities and configuration possibilities which when correctly specified will yield high reliability and long life.

Other conditions that should be considered besides these common ones just discussed are listed in Table 2-1. Each transducer type can differ greatly regarding all these considerations.

3. ENCODERS

Encoders are mechanical to electrical transducers whose output is derived by “reading” a coded pattern on a rotating disk or a moving scale. Encoders are classified by the

- method used to read the coded element: contact or non-contact
- type of output: absolute digital word or series of incremental pulses
- physical phenomenon employed to produce the output: electrical conduction, magnetic, optical, capacitive

CONTACT ENCODERS

Contact encoders are those which employ mechanical contact between a brush or pin sensor and the coded disk. The disk contains a series of concentric rings or tracks which are thin metallic strips joined at their base as shown in Figure 3-1. The four tracks shown in Figure 3-1 represent a binary code consisting of 2^0 , 2^1 , 2^2 , 2^3 . The associated contact sensors are identified at B_0 , B_1 , B_2 , B_3 , and encode the numerals 0 through 15. As the disk rotates, the sensors alternately contact conductive strips and adjacent insulators, producing a series of square wave patterns.

Uniform and non-uniform disc patterns can be utilized depending on the application. Virtually any pattern which can be produced photographically can be imaged on an encoder disc. The typical application is measurement of shaft position which utilizes a uniform pattern. Any non-uniformity in the disc is a source of error. Non-uniform segment spacing produces position error and eccentricity causes an error which is a sinusoidal function of the shaft angle.

Performance specifications are limited for factors such as, practical segmenting limitations on discs, bridging of disc segments, and wear of contacts.

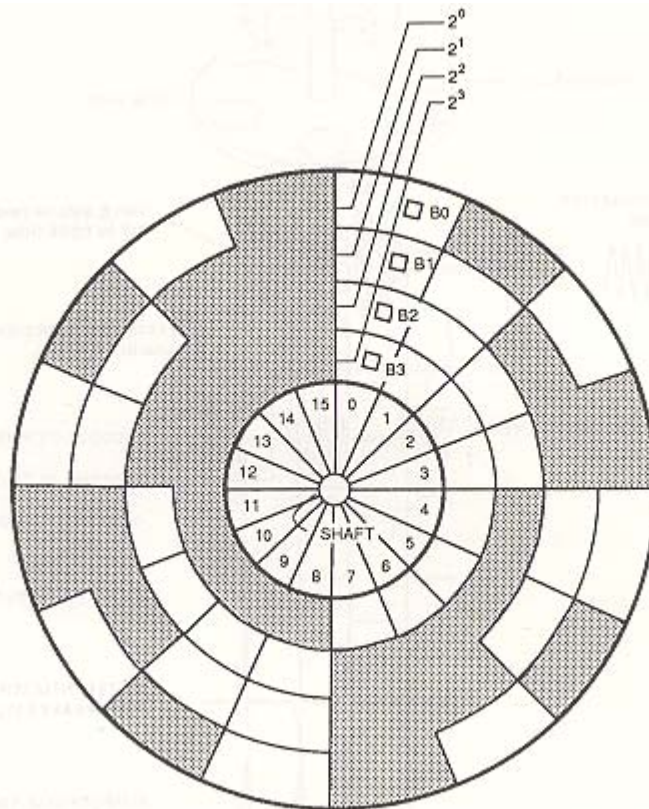


Figure 3-1. Absolute Contact Encoder Disk

NON-CONTACT ENCODERS

Non-contact encoders are those which employ physical phenomena other than electrical conduction to read the coded disc. The most common types are magnetic, capacitive, and optical.

Magnetic Encoders

Magnetic encoders were developed to replace contact encoders in applications limited by rotational speed. Magnetic encoders operate by detecting resonant frequency change, a magnetization change, or a magnetic saturation in an inductor. For each method, flux induction by the magnetically coded disc affects the change by aiding or inhibiting an existing state. Thus, for each principle, two normal states exist corresponding to a logical one or zero.

The resonant frequency type utilizes a tuned circuit, the frequency of which represents one logical state, and the detuning of the circuit representing the opposite logical state.

In the magnetic saturation method, the inductor is either saturated or nonsaturated. Alternately, the reluctance of the magnetic circuit is effectively translated to logical ones and zeros.

Resolution is limited by the size of the magnetized spot and complicated by interaction between magnetized spots on adjacent tracks. Magnetic encoders overcome the basic speed limitation of contact encoders and offer greater longevity by eliminating physical contact between disc and sensor. Also, magnetic encoders function well in environments hostile to contact types where any of the magnetic scanning techniques can be successfully employed. However, high ambient fluxes or radiation densities can destroy the disc pattern or inhibit saturated core operation. Greater precaution against mutual electromagnetic interference is required when magnetic encoders are included in the system. Figure 3-2 illustrates the principle stages of typical magnetic encoding.

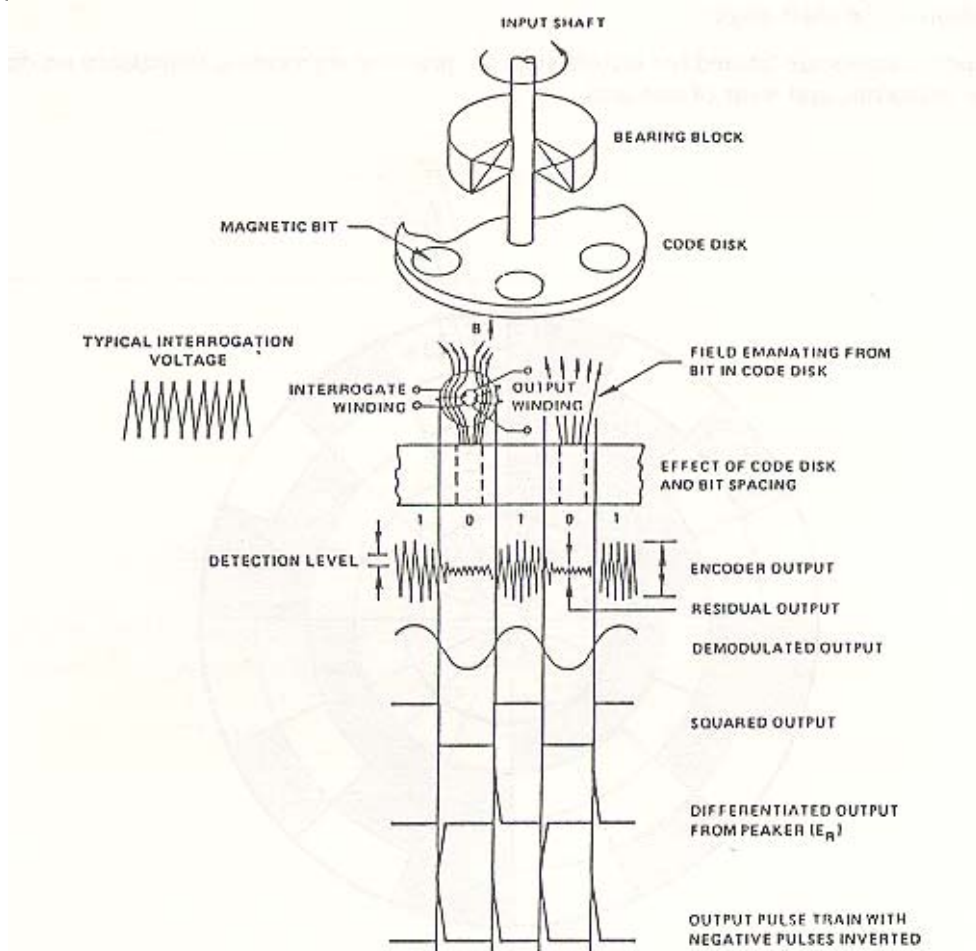


Figure 3-2. Typical Magnetic Coding

Capacitive Encoders

Capacitive encoders are the least used of the non-contacting types and were developed in response to unique needs. Readout is effected electrostatically using a phase shift measuring system or a frequency control technique to develop the digital output.

Although capacitive devices are not generally available as standard hardware, up to 19-bit, single turn units have been produced. Theoretically, the capacitive technique can be used to accomplish any of the encoding tasks performed by the contact, optical, or magnetic type. However, practical problems of design, manufacture, and operation have limited the use of capacitive detection.

Optical Encoders

The optical encoder was the earliest of the non-contact devices developed to eliminate the wear problems inherent with contact encoders. Present day optical encoders provide the highest resolution and encoding accuracy and can be operated efficiently at high speeds.

Optical encoder discs have opaque and transparent segments (see Figure 3-3). The discs can be produced by exposing a photographic emulsion to light, by plating metal on the substrate or by etching segments into a metal substrate. Each type has characteristics that may make it preferable in certain applications.

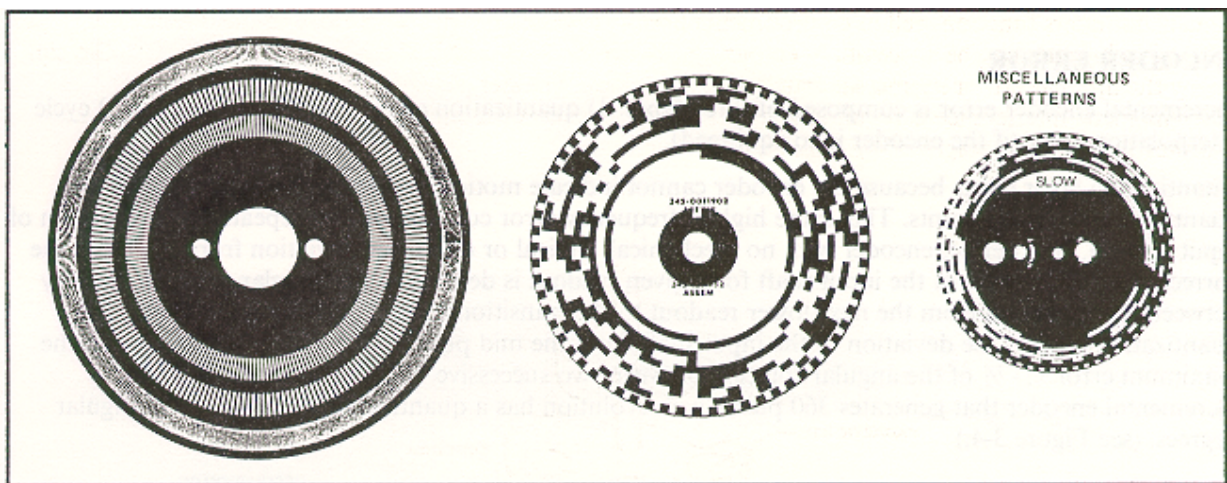


Figure 3-3. Encoder Disks

Readout is effected by an array of carefully aligned photoelectric sensors positioned on one side of the disc. A light source on the other side provides excitation. As the disc rotates in response to an input variable, the opaque area on the disc passes between the light beam modulating the sensor output in accordance with the selected code. Optical systems focus the light on the sensors. Light columnating LED's, mirrors, prisms, lenses, fiber optics, laser diodes, and optical slits or diffraction gratings perform this function.

Light detection can be performed by one of several devices. Materials for all types of light detecting devices are selected from groups III, IV, V of the periodic table and lie halfway in the spectrum between metals and non-metals. As such they are semiconductors. Each device responds to light in a different manner., Silicon or selenium based photovoltaic cells generate an electric current when exposed to light. The resistance of photoconductive cells varies with light intensity. The composition of photoconductive devices is usually cadmium sulfide or cadmium selenide, depending on the desired response of the device or the portion of the light spectrum for which sensitivity is desired. Current capabilities varies with the intensity of light. Photodiodes are similar to photoconductive cells. Photodiodes are used because their very small surface areas allow very high frequency response. They are generally run with back bias and the reverse leakage current is modulated with the light.

Phototransistors are photodiodes with built-in transistor amplification. Photodiodes have better frequency response and are less sensitive to temperature than phototransistors. In phototransistors, silicon controlled rectifiers (SCR's) act as sensitive high current switches when exposed to light.

Light sources for optical encoders may be solid state or incandescent, depending on the manufacturer's design and application of the encoder.

Recently, enhancements to optical encoder operating performances has strengthened its position in the motion control markets. Ongoing improvements in resolution capabilities, frequency response, accuracy, mechanical bearing assemblies, and environmental packaging serve to maintain the optical encoder as the dominant choice for feedback devices.

INCREMENTAL VS. ABSOLUTE OUTPUT

In a preceding discussion, reference was made to a coded disc pattern like that in Figure 3-1, for which the encoder output is a digital word representing the absolute angular position of the encoder shaft; hence the designation absolute encoder.

If the coded disc pattern is replaced with a uniform pattern such as a series of equally spaced radial lines, encoder output becomes a series of incremental pulses that can be counted to determine shaft position relative to some reference point. This configuration is called an incremental encoder. This type routinely provides zero reference and dual channel outputs for homing and direction sensing functions, respectively.

Comparatively, there are strengths and weaknesses to each device. The absolute encoder does not have to be homed after a power loss or noise burst. Incrementals are simpler to use and less expensive.

ENCODER ERROR

Incremental encoder error is composed of three types: 1) quantization error, 2) instrument error, 3) cycle interpolation error (if the encoder is so equipped).

Quantization error exists because the encoder cannot indicate motion occurring within one resolution quantum at transition points. This is the highest frequency error component and repeats every quantum of input motion. In a perfect encoder with no mechanical, optical or electronic deviation from the ideal, the correct angular position of the input shaft for a given readout is defined as the angular position midway between the transition from the next lower readout to the transition for the next higher readout. The quantization error is the deviation of the input shaft from the mid position for a given readout, with the maximum error $\pm 1/2$ of the angular rotation between two successive bits. For example, a rotary incremental encoder that generates 360 pulses per revolution has a quantization error of $\pm 1/2$ angular degrees (see Figure 3-4).

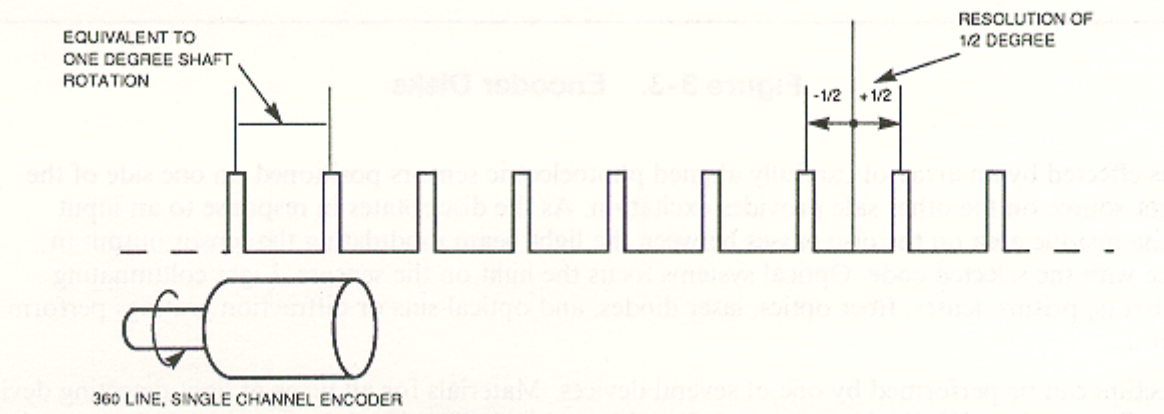


Figure 3-4. Encoder Resolution

Instrument error is the sum of disc and reticle pattern errors and mechanical imperfections within the encoder. Factors such as bearing types, line to space ratio tolerances, substrate flatness, optical setup, and encoder alignment contribute to this type error. Manufacturers will usually specify these types of errors and quantify them relative to specific encoders or encoder groups.

Cycle interpolation error (if the encoder is so equipped) is due to imperfections in the analog signals from the photodetector and their subsequent processing. These imperfections consist of phase shifts or dc offsets in the quadrature encoder signals that create position errors in the signals zero crossings, which affect

the count produced by a given amount of movement, as zero crossings are counted as a measure of movement. The effect of these errors are magnified by interpolating a line cycle into smaller increments of motion. To minimize such errors, disc line counts should be kept as high as possible to allow usage of the lowest possible interpolation factor. In general, cycle interpolation error is about one-half quantum (resolution interval) for higher interpolation factors and one-eighth quantum for lower interpolation factors.

4. THE OPTICAL INCREMENTAL ENCODER

As noted in the preceding sections the optical incremental encoder is widely used to monitor rotary and linear motion. In this section, the encoder manufactured by DRC will be described and the major advantages of its design will be discussed.

THEORY OF OPERATION

The principle of incremental encoder operation is generation of a symmetric, repeating waveform that can be used to monitor the input motion. The basic components of all optical incremental encoders are the light source, light shutter system, light sensor, and signal conditioning electronics. These components will be housed and assembled to various mechanical assemblies, either rotary or linear in design depending on how motion will be monitored. The encoders mechanical input operates the light shutter which modulates the intensity of the light at the sensor. The sensors electrical output is a function of the incident light. The encoders electrical output is produced from the sensor output by the signal conditioning electronics and can be either

- a sinewave
- a shaped, squarewave
- a series of equally spaced pulses produced at regular points on the waveform

In its most fundamental form, the light shutter is an optical slit and a substrate inscribed with alternating lines and spaces of equal width. When the substrate is moved relative to the slit, the light transmitted through the slit rises and falls. This incident light relatively excites the light sensor which in turn provides the raw electrical signal to shaping electronics. In practice, a large multi-slit stationary substrate or reticle, is used instead of a single slit (see Figure 4-1). The reticle allows transmission of more light which aids the alignment process. Also, line imperfections such as pinholes, scratches, and dust particles do not significantly affect sensor output since incident light is averaged over many lines.

The encoders mechanical input is coupled to the moving plate to operate the light shutter. For the position shown in Figure 4-1, the light sensor will indicate maximum light intensity.

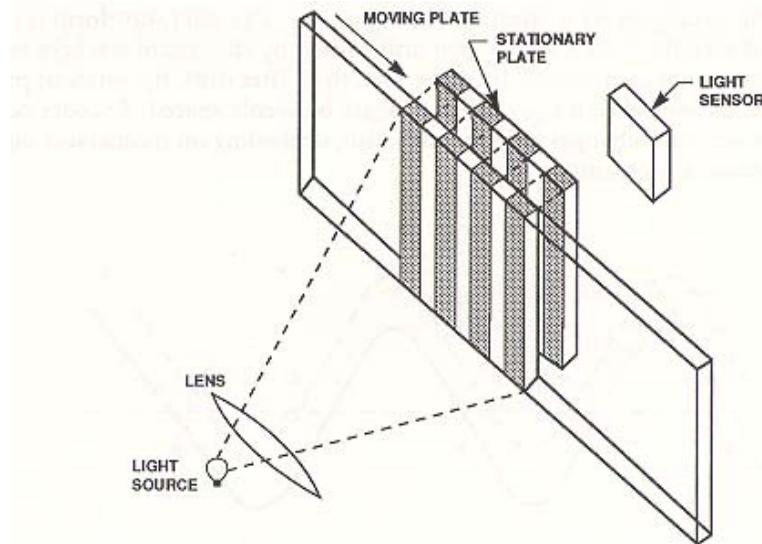


Figure 4-1. Light Shutter

After the moving plate has advanced one line width the opaque lines on the moving plate will cover the transparent lines on the stationary plate and light transmission will be minimum, theoretically zero. In practice, the light source can't be fully collimated and some clearance must be maintained between the stationary and moving plates. Consequently, some light will leak through the shutter when in its fully closed position and the minimum light transmission will be nonzero.

Waveform of the sensor output is theoretically triangular (see Figure 4-2) but is, in practice, more nearly sinusoidal. e_{\max} depends on output of the light source, shutter transmission when fully open and sensitivity of the sensor. e_{\min} depends on shutter leakage when fully closed. e_1 , the peak-to-peak voltage, is the usable component of sensor output and is limited by the effectiveness of the shutter mechanism to minimize shutter leakage. Collimating the light source, locating the stationary substrate close to the sensors, and gap between disc and reticle have an effect on shutter leakage.

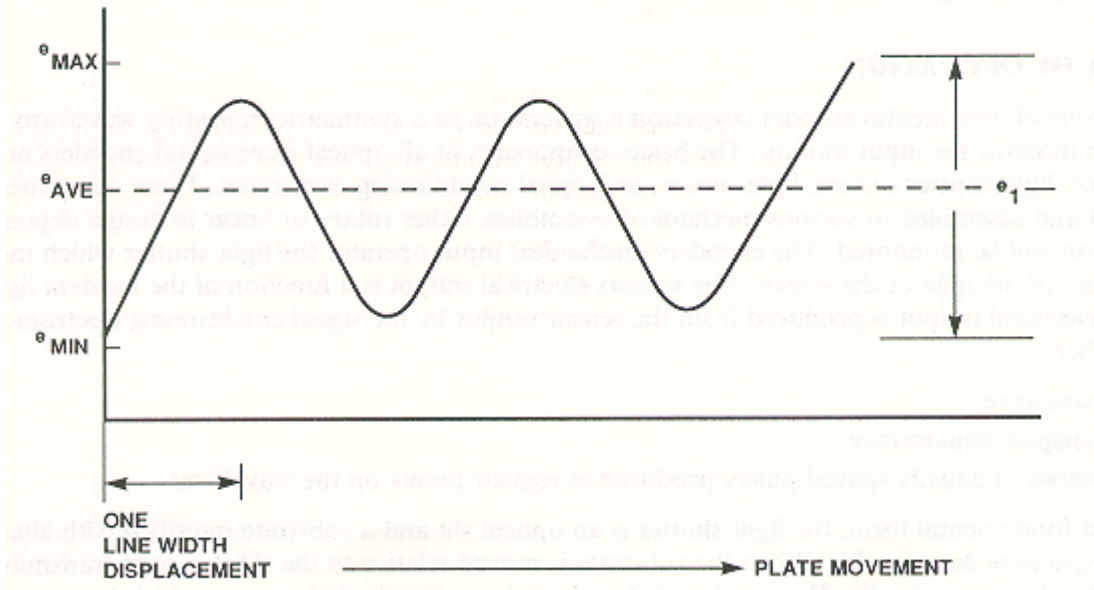


Figure 4-2. Detector Output

A common method of digitizing encoder output is to produce a pulse each time the waveform of Figure 4-2 passes through its average value, e_{AVG} . Ideally, the waveform crossings are equally spaced and correspond to one line width displacement of the moving plate. The resulting series of equally spaced pulses can be used to precisely monitor the encoders mechanical input.

The primary problem with this arrangement is illustrated in Figure 4-3. The solid waveform. is the same as that of Figure 4-2. The dotted waveform. represents signal drift caused by changes of the light sources excitation voltage or sensitivity of the light sensor. It can be seen that, after drift, the series of pulses generated when the waveform, passes through e_{AVG} will no longer be evenly spaced. Encoder performance degrades because pulse width accuracy changes significantly. Also, depending on mechanical input speed, frequency response could become a problem.

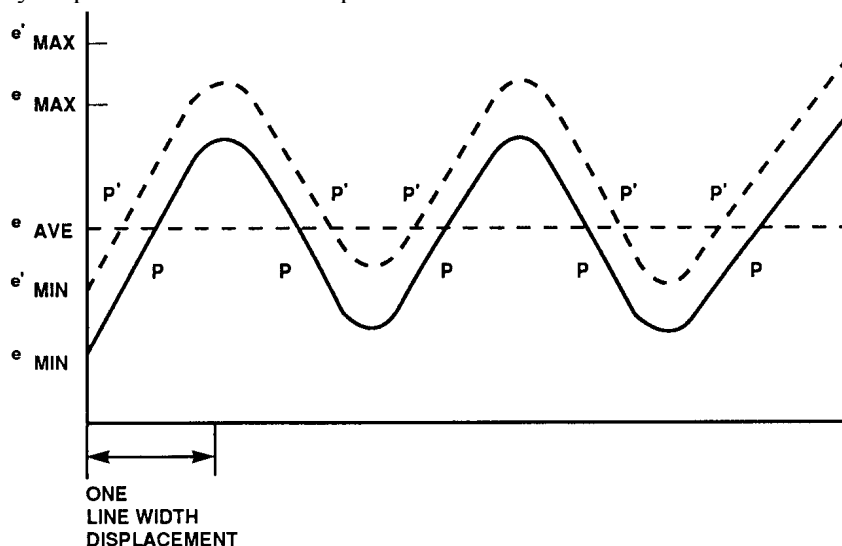


Figure 4-3. Effect of Signal Drift on Spacing of Encoder Pulses

Compensation for signal drift is achieved with another sensor in combination with the same moving plate. The stationary component of the shutter of the second sensor is fixed 180 electrical degrees out of phase with respect to the stationary plate of the first sensor. The same light source illuminates both shutters (see Figure 4-4). When maximum light is incident on the first sensor, the second sensor has minimum incident light. Simultaneous incident light intensity on the two sensors is out of phase. Thus, the resulting electrical outputs will be out of phase as in Figure 4-5. The resultant waveform when the two sensors are connected in opposition (i.e., push-pull or head-to-tail) is the equivalent of algebraically subtracting the output of sensor No. 2 from sensor No. 1 as shown in Figure 4-6.

Several characteristics of the resultant waveform are important. First, its average value is theoretically zero. (In fact, the inevitable mismatch between the two waveforms results in some small deviation from zero. This deviation can be suppressed with an external bias voltage.) Second, the peak-to-peak voltage is now twice that of the separate sensors. This means that change of interpulse spacing for a given shift of the resultant waveform (like that in Figure 4-3) is only half of what it would be for the same single sensor.

This push-pull arrangement further improves encoder operation by reducing the effects of changes in light excitation voltage and detector sensitivity. Any light intensity change that affects both sensors equally will cancel. Likewise, equal detector sensitivity changes will cancel.

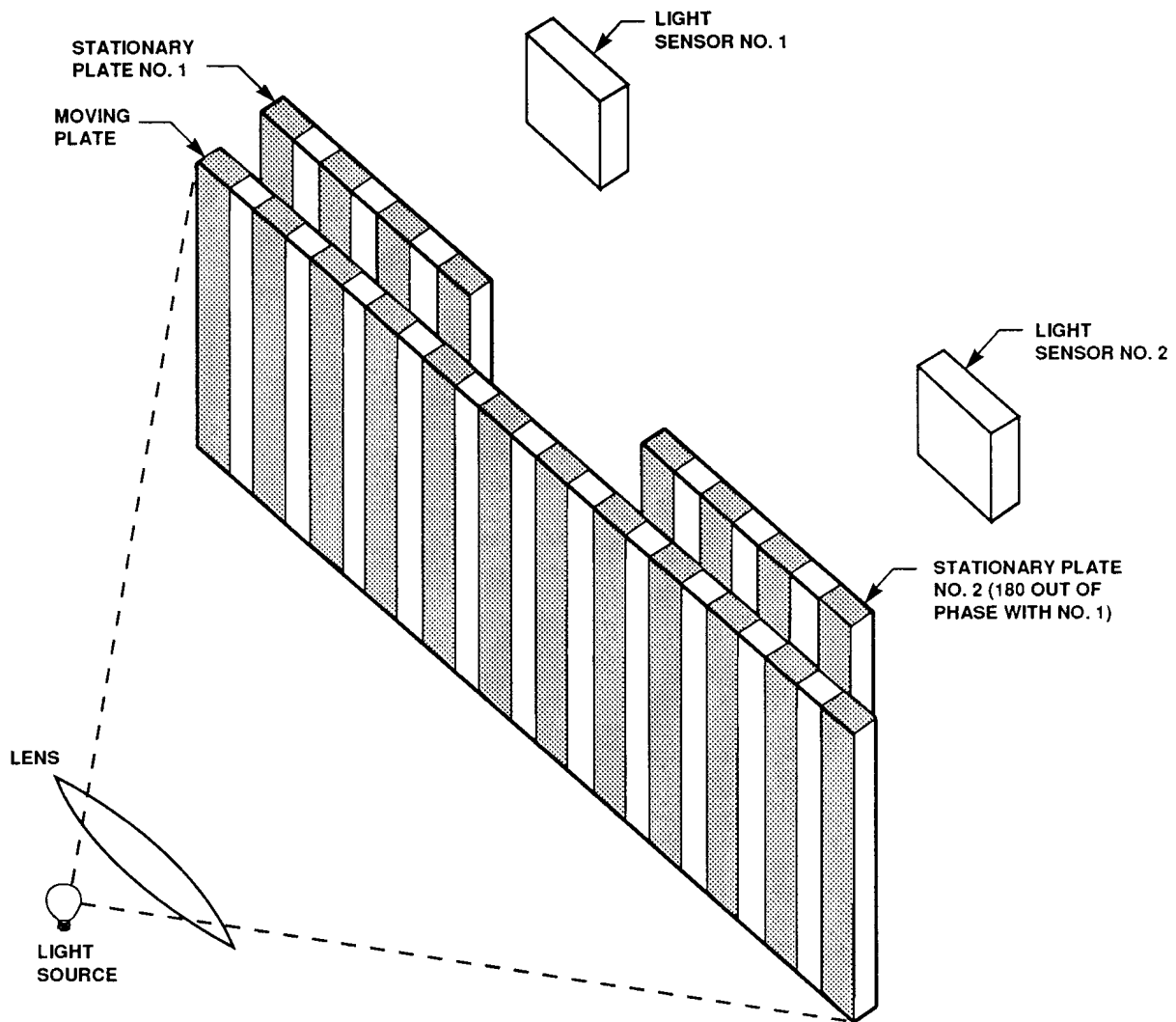


Figure 4-4. Two Cell Arrangement for Signal Drift Compensation

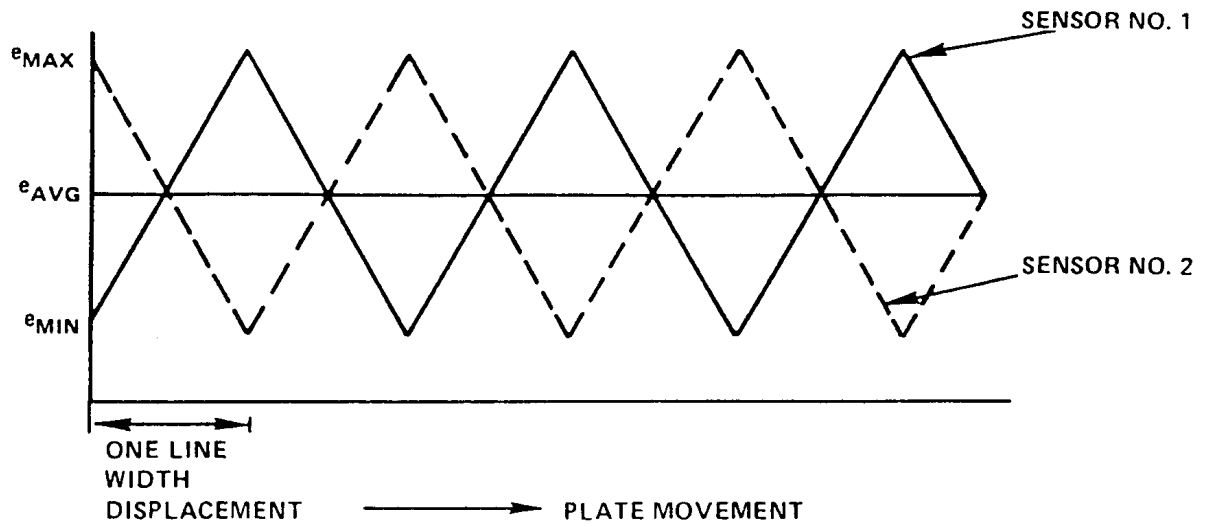


Figure 4-5. Outputs of Two Sensors Fixed 180° Out of Phase

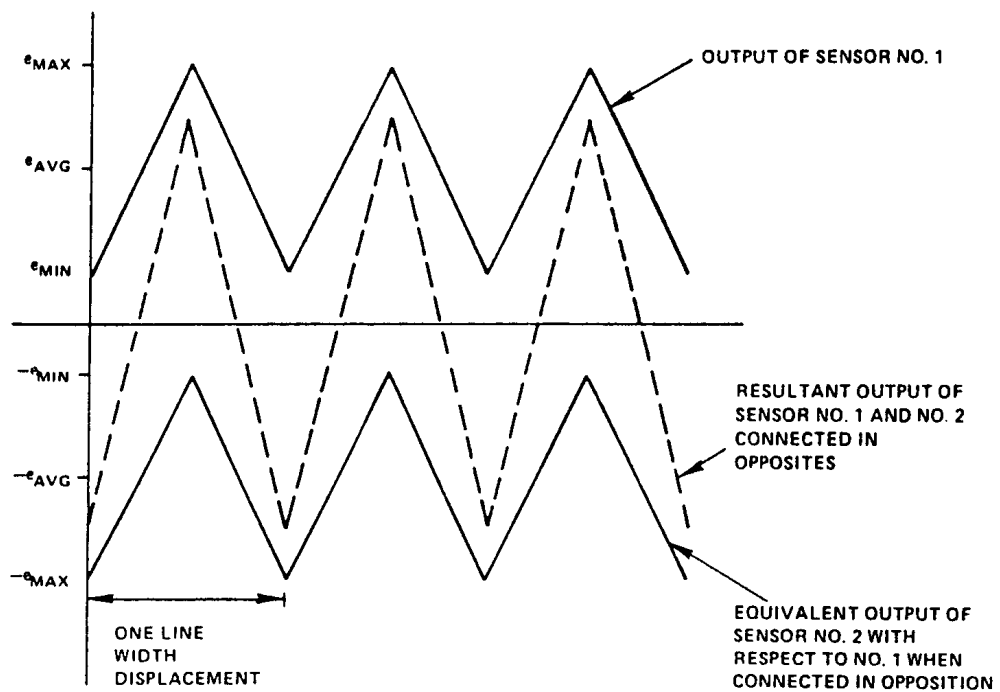


Figure 4-6. Outputs of Sensors No. 1 and No. 2 Connected in Opposition

The output signal just described is called, *single channel output*. Typically, encoders have two channels. The second output is produced with another pair of sensors displaced electrically 180° from each other and 90° from each of the sensors of the first channel, or channel A. The resulting waveforms are shown schematically in Figure 4-7. Interpulse spacing for the two channel encoder represents movement of one half line width. Therefore, any line/space pair (1 cycle), in conjunction with a two channel output, produces a “quadrature signal.” This means four pulses can be detected per cycle. The highest possible resolution of an encoder with a 1024 line count disc and two channel output is $4 \times 1024 = 4096$ pulses per revolution. The average angular displacement represented by a single pulse is 5.27 minutes of arc.

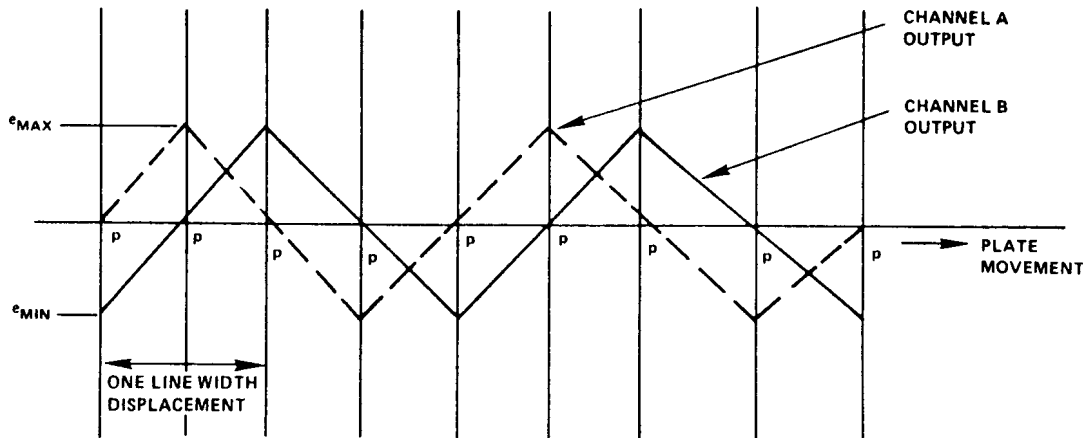


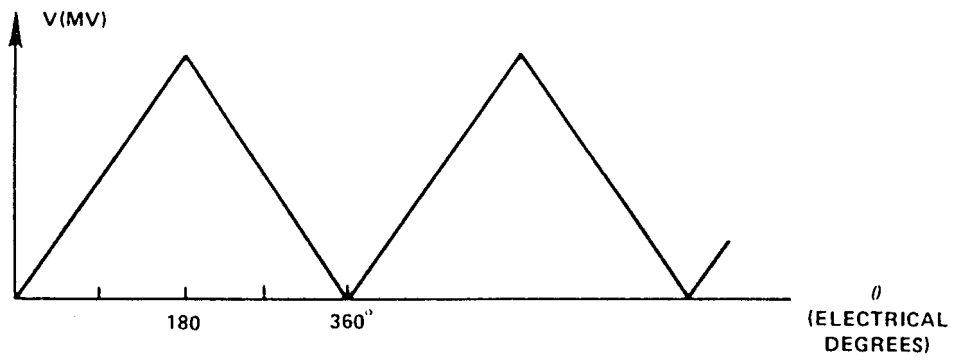
Figure 4-7. Dual Channel Output Phased in Quadrature

The sensors used in DRC encoders are large area silicon junction diodes commonly called cells. To obtain the ideal waveforms shown in Figure 4-7, the cells connected in the push-pull arrangement must track one another. That is, equal changes in input must produce equal output changes. When the components do not track there will be a symmetry shift in the resultant waveform like that depicted in Figure 4-8C.

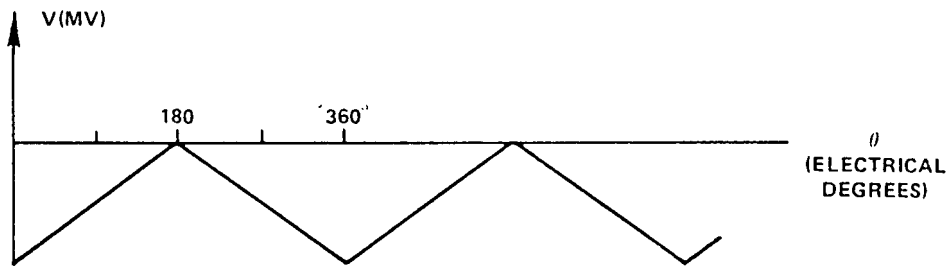
Symmetry is defined as the condition where the zero dc level of the output waveform divides the waveform into two states of equal duration when the encoder shaft is rotated at constant speed. That is, the waveform is symmetric if it has a zero mean value. If the mean value is not zero, the dc level which divides each cycle of the waveform into equal parts is the symmetry level. This unbalanced condition causes the zero crossing to shift markedly. Symmetry shift in a given channel is minimized by

- using cells of equal temperature and light sensitivity
- using one light source to illuminate all sensors
- placing the cells as close together as practical
- using signal trimming techniques to balance output

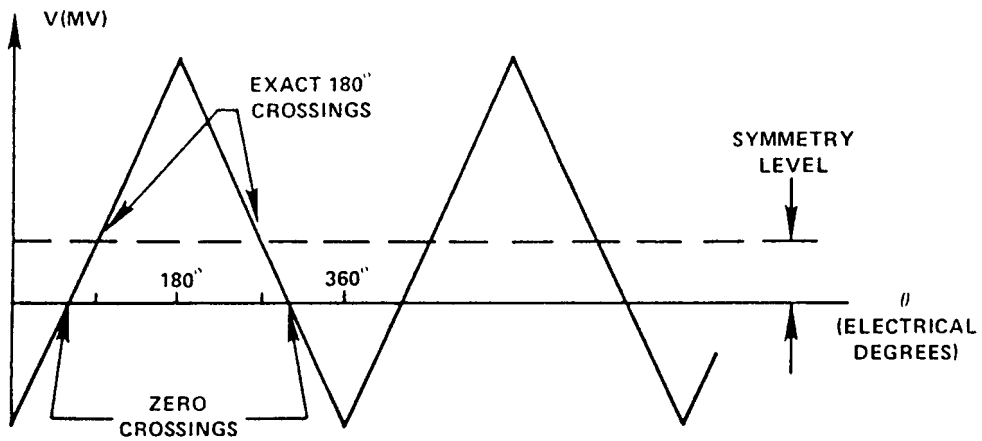
Another important characteristic of silicon cells is frequency response. Frequency response depends on load resistance and cell size. The output of a pair of 0.200 in. \times 0.050 in. cells can drop 10% to 25% when operated into a 1000 ohm load at 50 KHz. This does not limit the maximum usable cell frequency to 50 KHz. What is important is the shift in zero crossing with frequency. With a perfectly balanced channel the zero crossings are unchanged. However, with an unbalanced pair of cells, the shift may be appreciable at high speeds because the outputs of the two cells drop unequally. The average output from each individual cell of a back-to-back pair does not change with frequency. However, as the ac components fall with frequency, any unbalanced dc component becomes more significant having the effect of increasing phase error. Figure 4-9 illustrates the output of typical cells and the resultant output signal at low and high frequency operation. The average value of each cell remains the same regardless of frequency, but the peak-to-peak output changes. The two resultant waveforms show that the symmetry level remains the same. At low frequency, the 180° crossing is shifted by 10 electrical degrees. This error can be reduced by inserting a fixed dc signal of equal magnitude but opposite polarity to the symmetry level.



a. CELL NO. 1 OUTPUT VOLTAGE



b. CELL NO. 2 OUTPUT VOLTAGE



c. RESULTANT OUTPUT FROM CELL NO. 1 AND CELL NO. 2 IN PARALLEL

Figure 4-8. Result of an Unbalanced Pair of Solar Cells

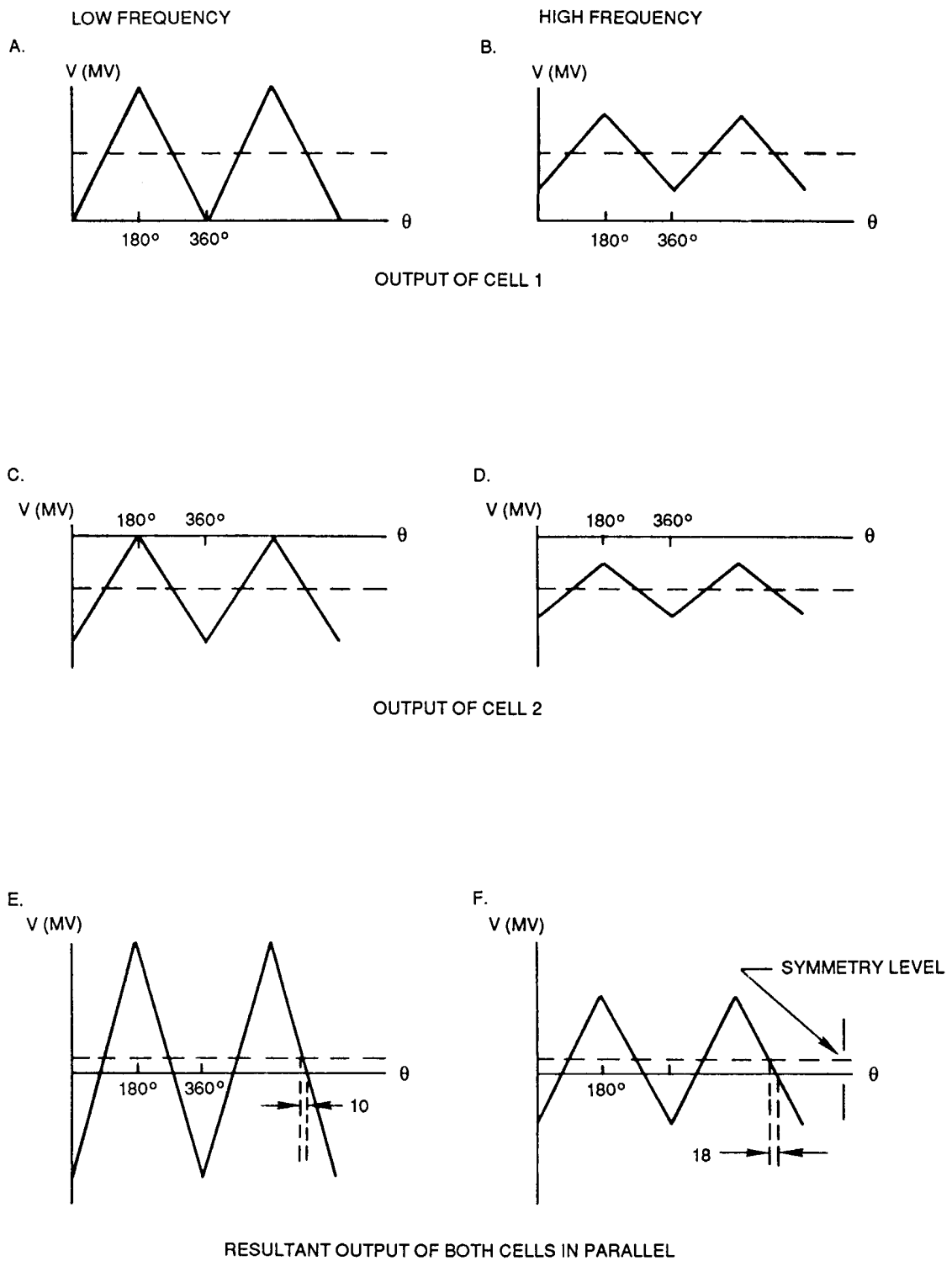


Figure 4-9. Typical Frequency Response of a Pair of Unbalanced Cells

COMPONENT DESCRIPTIONS

The following is a detailed description of the major encoder components and the significance of these on encoder performance.

Light Sensor

The sensor used in most applications is a photovoltaic, wide area, silicon cell. Figure 4-10 shows the construction of the silicon cell. At the heart of the sensor is an area of single crystal, "N" type, silicon material with a "P" type layer diffused into it. This crystal generates an output when illuminated. Electrical connections are made to the crystal and the signal is transmitted over the leads.

Light energy is comprised of small energy packets called photons. When a photon containing sufficient energy strikes a silicon crystal, a hole-electron pair is created. This pair diffuses and is collected by the P-N junction. When large quantities of photons are involved, a voltage difference appears between the "P" and "N" regions. When a load is connected across the crystal, the voltage potential causes a current which is supplied by the light generated hole-electron pairs.

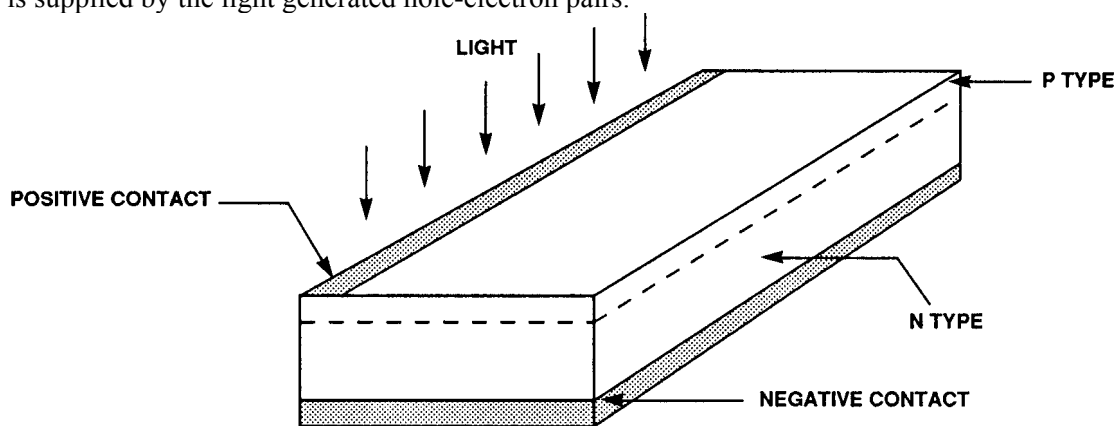


Figure 4-10. Solar Cell Construction

The silicon cell has several advantages over other photosensitive materials. Unlike the photodiode and phototransistor, operation of the silicon cells requires no external voltage. Further, the silicon cell is a current source and matches the transistor input characteristic. Spectral response of the silicon cell, shown in Figure 4-11, is relatively broad and is well matched to the outputs of both tungsten filament lamps or the light emitting diode. The silicon cells coefficient of output signal versus light intensity in the infrared region is greater than that of any other candidate material. Frequency response of the silicon cell is excellent, and silicon is resistant to most environmental hazards.

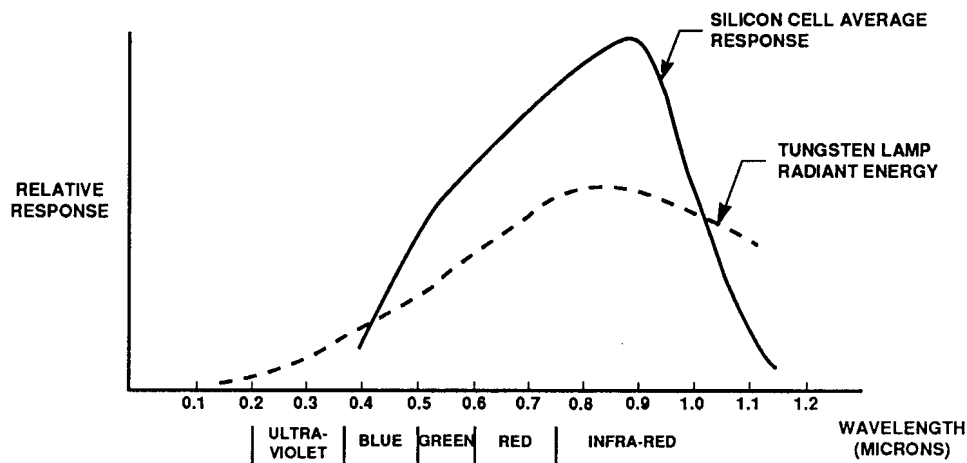


Figure 4-11. Spectral Response of Silicon Cell and Spectral Distribution of Tungsten Lamp

Light Source

Both lamps and light emitting diodes (LEDs) are used in encoders. Lamps offer greater light output than LEDs but are less reliable in many applications. Mainly, operating life for a lamp is 40,000 hours versus 100,000 for an LED.

Table 4-1 compares the relative merits of each device.

Table 4-1. Light Sources

	LAMP	LED
Life	40,000 hrs.	100,000 hrs.
Output	High	½ lamp
Output vs. Temp.	None	High
Shock & Vibration	Moderate	Good
Temp. Cycle Damage	Moderate	Low
Output Var. vs. Voltage	High	Moderate
Max. Oper. Temp @ Rated power	200°F	150°F

In comparison to these critical characteristics, it is evident that the LED is preferable in most encoder applications. Superior durability, longer operating life and lower cost are typical of most LEDs. Although LEDs are more temperature sensitive and provide less light output than tungsten filament lamps, these characteristics are compensated for by improved detection and amplifying circuitry. For these reasons, DRC uses LEDs exclusively in their products.

Shutter

Another critical component assembly of the encoder is the shutter mechanism. The precision to which this assembly can be manufactured is the basis for accuracy and resolution of the encoder. The basic components of the shutter assembly are the disc, reticle, shaft, bearings, and housing.

The disc and reticle set can be produced using various substrate material. The most common material is glass. Other substrate materials include metal and plastic. Each type material possesses characteristics which influences its use in a particular application. For instance, glass is used where high degrees of accuracy is required because it can be lapped very flat and has lower thermal expansion characteristics. Metal is used where durability is most important and resolution is not a major factor. Plastic discs have similar resolution capabilities as glass but is not as accurate.

The density of lines and spaces on a given substrate is largely limited by diameter or thickness, depending on what material is used. Evaporation or etching processes are used to place the line patterns on the substrates. Either photo emulsion or metal film with higher precision (line definition). The cost of the metal film is generally higher. Resolution range for metal substrate units, which utilizes etched slits in the metal, is limited due to minimum flatness requirements required for efficient shuttering. Disc sagging occurs as the resolution increases proportional to the thickness of the substrate.

Centerless ground stainless steel is used for shaft material in all DRC integral shaft and bearing encoders. Often finished turned to within .0002" T.I. R., a precision shaft enhances the accuracy of the encoders shuttering mechanism.

Bearings are stainless steel, prelubricated with various oils or greases and can be provided in multiple ABEC levels. Different diameters of inner and outer races are specified depending on loading specifications on the encoder shaft. The shaft and bearing assembly are normally manufactured utilizing preloaded bearing pairs in order to minimize axial and radial shaft movement and set torque levels.

The assembly of the above components onto a housing or base, represents the shutter mechanism. Final alignment of the disc and reticle to the center of rotation (shaft and bearing assembly in a rotary device) can be done either optically or electrically. Concentricity of the disc pattern can be held within .000050" to the center of rotation using either of these methods. If the encoder is a linear device, parallelism and perpendicularity of the scale and reticle to the axis of travel is required for proper shutter function.

Mounting the encoder has an effect on the shutter action as well, especially for encoders that require the customer to set the gap and run out to specification. Modular encoder types rely on the motor shaft to meet run out specs and generally emulate the shaft of integral shaft encoders. Most linear devices require precision alignment in order to ensure proper functioning and the highest possible accuracy. Coupling of the mechanical input influences the shutter action as well. This will be discussed in greater detail in the next chapter. Figure 4-12 illustrates the basic components of the shutter mechanism.

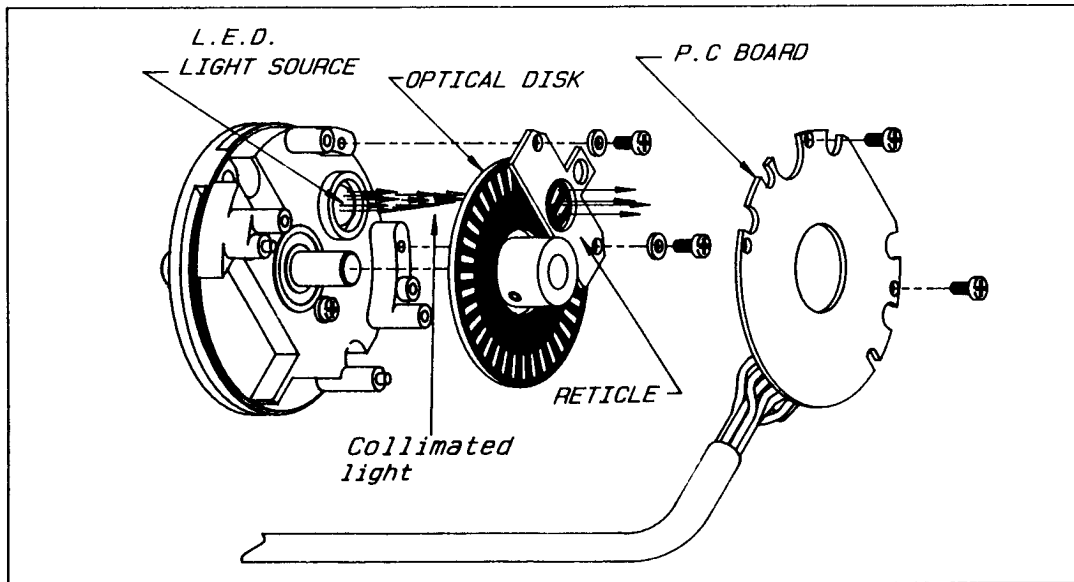


Figure 4-12. Basic Components of the Shutter Mechanism

Signal Conditioning Electronics

Encoder electronics perform the following functions

- generation of the output signal waveform
- generation of complimentary signals
- direction sensing
- resolution enhancement
- filtering

The available output waveforms are illustrated in Figure 4-13.

The sinewave or cell output signal is illustrated in Figure 4-13A. Typically 20 millivolts peak-to-peak, this is the basic signal for subsequent processing.

The amplified analog waveform is illustrated in Figure 4-13B. This signal is an amplified version of cell output typically 2.5 volts peak-to-peak.

The TTL squarewave is illustrated in Figure 4-13C. The square waveform is produced with a shaper circuit consisting of comparators and other logic devices. The shaper has two stable output states which are controlled by the amplitude of the input voltage.

Shaper output is fed to gates which generate the pulses marking the encoder signal zero crossings (see Figure 4-13D). The quadrature signals are staged at this point to allow phase adjustment for count channels which provide direction sensing and controls pulse width.

Figures 4-14, 4-15, 4-16, and 4-17 represent schematics common to DRC encoders.

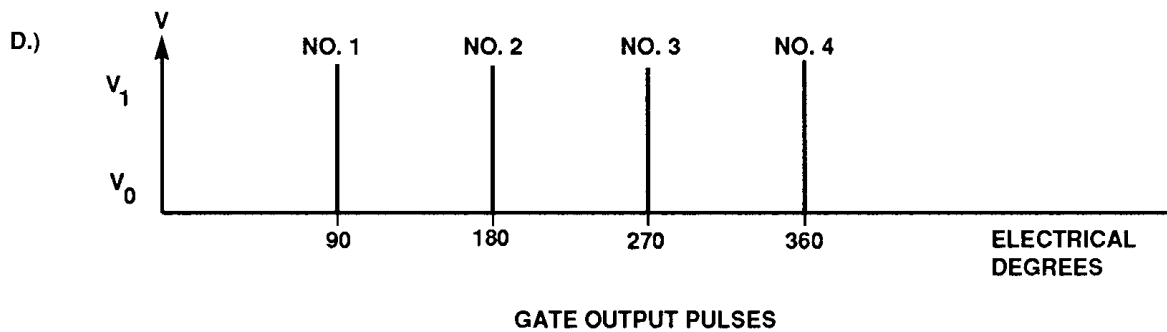
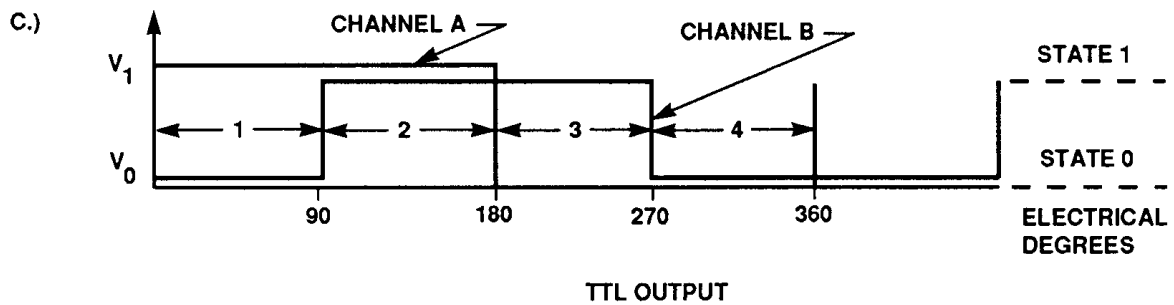
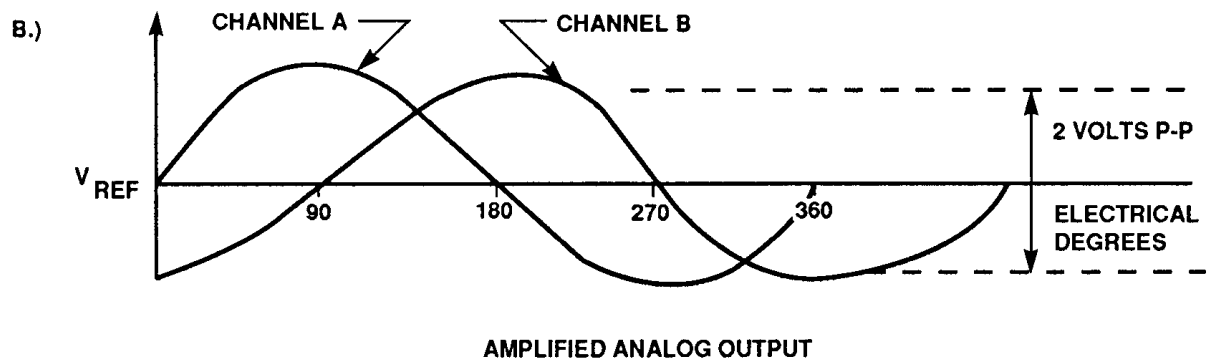
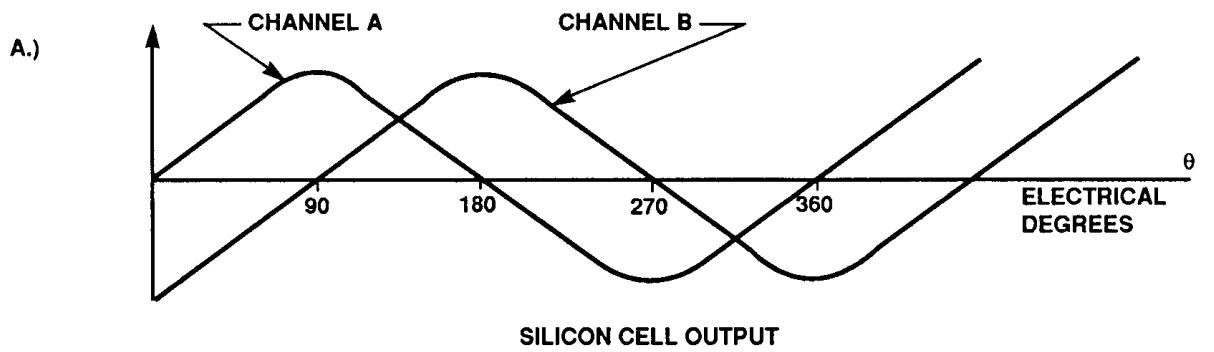


Figure 4-13. Encoder Output Signals

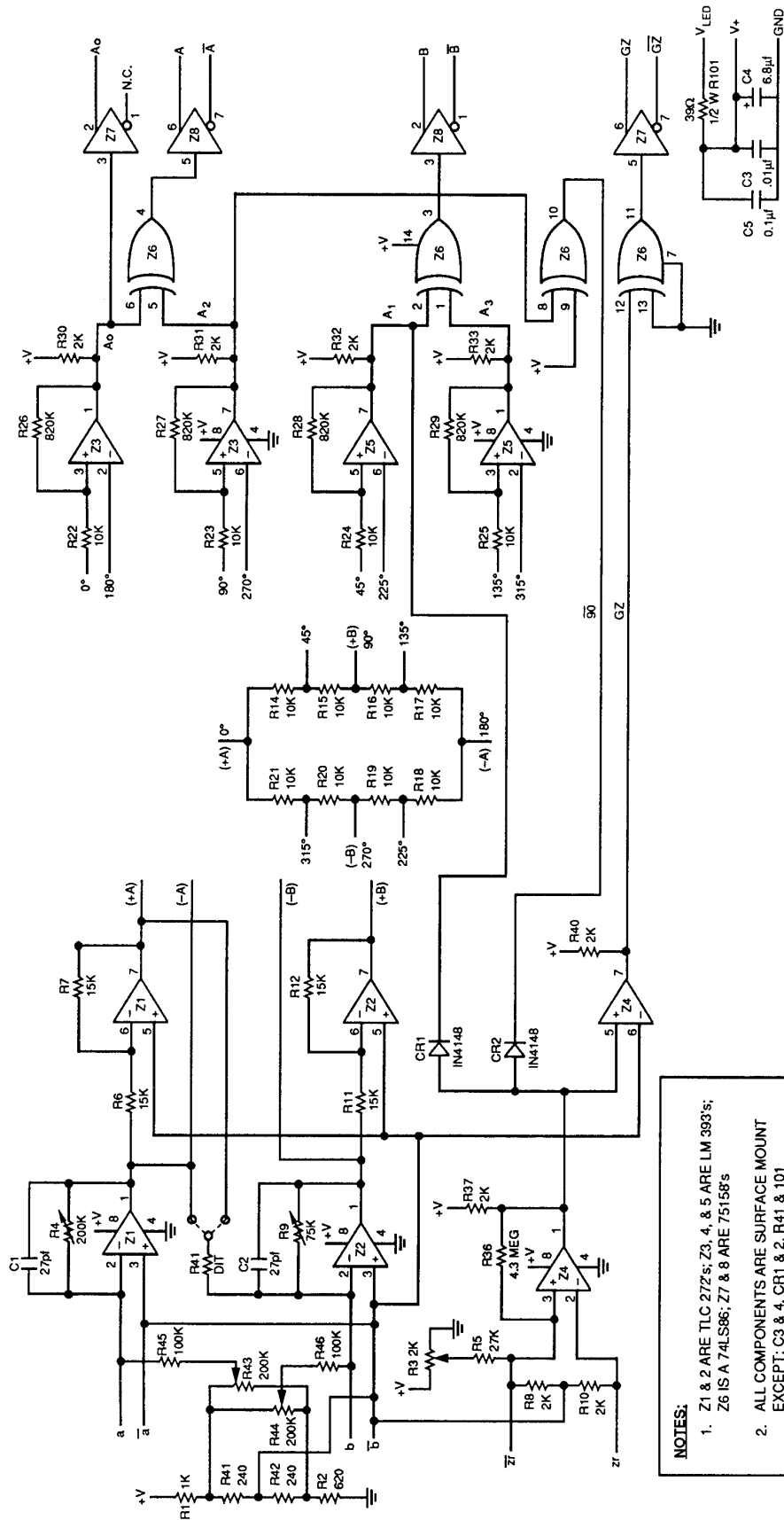
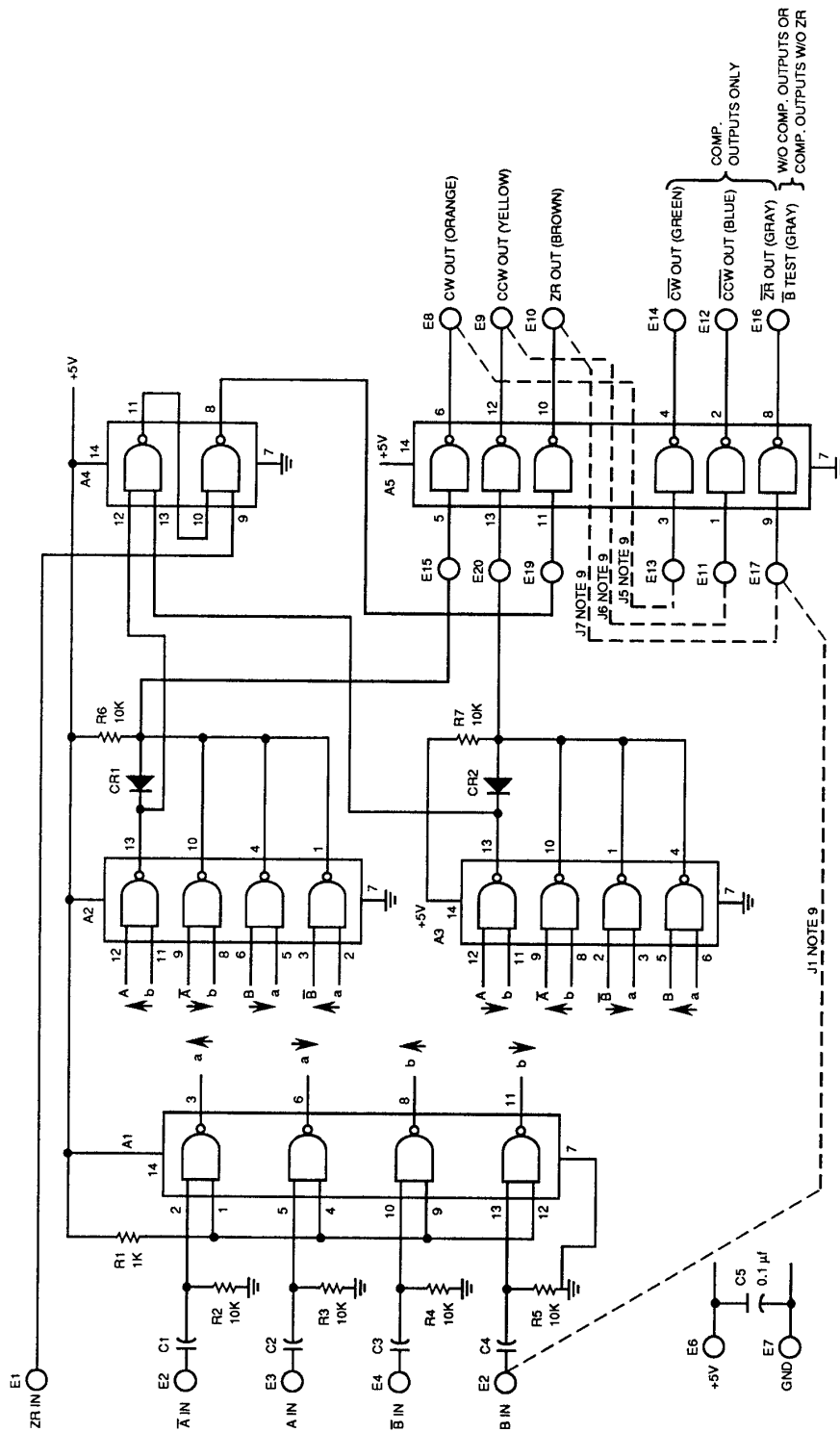


Figure 4-14. Schematic, 2X Interpolation, Lt



NOTES:

- ALL RESISTORS ARE 1/8 WATT ±5%
- ALL CAPACITORS ARE ±10%
- A1 IS A 9946
- A2 AND A3 ARE 7401
- A4 IS A 7400
- FOR 5V, 6V A5 IS A 7404
FOR 12V, 15V A5 IS A 7416

7. FOR 2X LOGIC OMIT C1, C2, R2, R3
FOR 1X LOGIC OMIT C1, C2, R2, R3; OMIT CR1 AND CR2, REPLACE

8. WITH JUMPERS J3 AND J4; JUMPER, J2, E2 TO E7

JUMPER	W/O COMP. OUTPUTS	COMP. OUTPUTS W/O ZR	COMP. OUTPUTS W/ ZR
J1	X	X	OMIT
J5	OMIT	X	X
J6	OMIT	X	X
J7	OMIT	OMIT	X

10. ASSY C-5306 FOR COMP. OUTPUTS ONLY

Figure 4-15. Schematic Logic Board (1X, 2X, 4X) Model 29, 35, 39, and 77

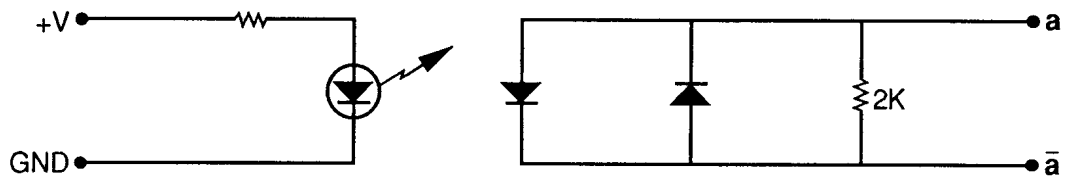


Figure 4-16. Typical Photodiode (Cell) Output Configuration

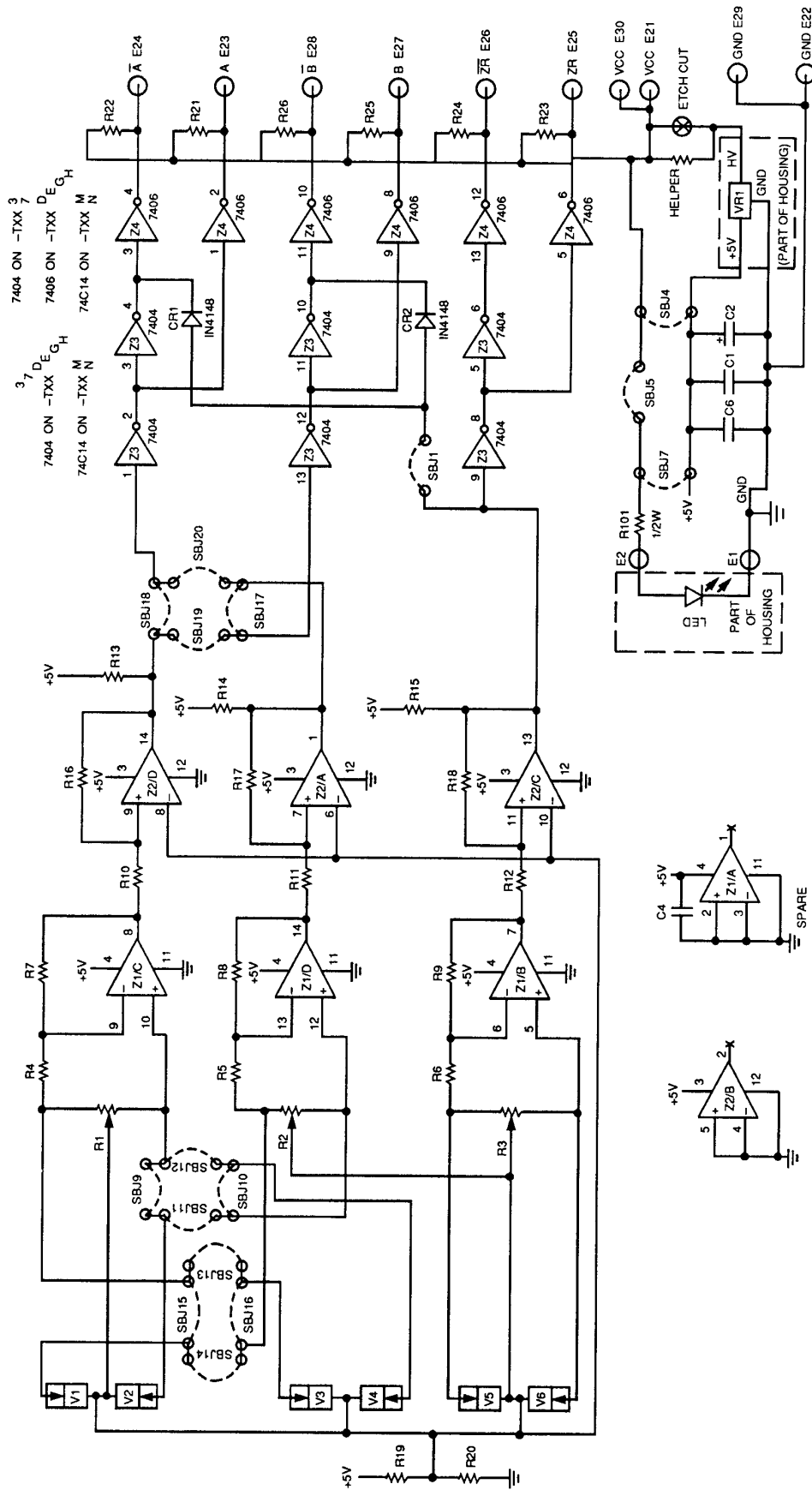


Figure 4-17. Schematic Diagram TTL/O.C. Board

5. ENCODER INTERFACE CONSIDERATIONS

This section is a discussion of the general electrical and mechanical considerations of interfacing DRC encoders within different systems. Manufacturer's product literature tends to be detailed, specific to one product, and is not generally appropriate for exploring design alternatives. The determinants of selecting an encoder will be outlined, reviewed, and recommendations made.

Whatever the encoder application, the following basic decisions must be made

- what signal level and waveform. will be used
- how the encoder output will be interfaced with the system
- whether a rotary or linear encoder will be used
- how will the encoder be mounted
- how the mechanical input will be coupled to the encoder
- how will the environment effect the encoder

SIGNAL LEVELS AND WAVEFORMS

Choosing the appropriate waveform. and signal level depends on such factors as cost, cable length, ambient noise environment, and compatibility with the rest of the system. These basic waveforms are illustrated in Figures 5-1 through 5-4. Figure 5-1 illustrates the sinewave or cell output type signal. This signal type can be either single channel or dual channel phased in quadrature. Dual channel output is necessary for direction sensing. Signal levels are typically 20 to 100 millivolts peak-to-peak, depending on load and output frequency. Sinewave output is normally employed if the user desires to save the expense of the internal electronics by having the signal shaped externally with respect to the encoder. However, this type of signal is susceptible to electrical noise. This condition can be improved by amplifying the sinewave and adding complementary channels, at increased cost. Figure 5-2 illustrates the typical TTL squarewave signal. Achieved by amplifying and shaping of the cell output signal, it has a nominal signal level of 5 volts. The "ON" state or logic level "1" is 2.4 volts minimum and the "OFF" state or logic level "0" is 0.4 volts maximum. A dual channel quadrature signal is required for direction sensing. Rise and fall times for squarewaves are 100 nanosec at no load and up to 1 microsecond at a 1000 picofarad load. Typical integrated circuits used for squarewave type signals are comparators, hex inverters, open collectors, and fine drivers. Each type has its own distinct characteristics which may make it the preferred choice in a particular application. The characteristics that are commonly considered when specifying an output type are sink and source current capabilities, single ended or complementary, input voltage range, speed of device, and cost of device(s). The line driver, not a true TTL device, is particularly effective for driving signals over long distances when used differentially. Open collectors can increase voltage levels by utilizing pull-up resistors. Comparators have a wide range for input voltages but limited sink and source capabilities. Hex inverters provide complementary channels. The selection should be based upon a thorough examination of the system requirements.

Pulse type output, shown in Figure 5-3, is available in 1, 2 or 4 count logic. Measured at 50% of the signal amplitude, the pulse width is typically 3 (\pm) microsec. This type of signal is noise susceptible, limited to relatively short cable lengths and difficult to use for direction sensing.

ELECTRICAL INTERFACE

The most frequent problems encountered in transmitting the encoder signal to the receiving electronics are signal distortion and electrical noise. Either problem can result in gain or loss of encoder counts. Imprecise monitoring of the mechanical input is the ultimate result.

Signal Distortion

Signal distortion is illustrated in Figure 5-5. The receiving electronics will respond to input signal that is either logical "0" (i.e., less than 0.4 volt) or logical "1" (i.e., greater than 2.0 volts). The region between 0.8 and 2.0 volts is logically undefined and the transition through this region must be very rapid (less than 1 microsec). As the leading edge of the waveform is distorted, the transition time increases. At some point the receiver becomes unstable and encoder counts must be gained or lost.

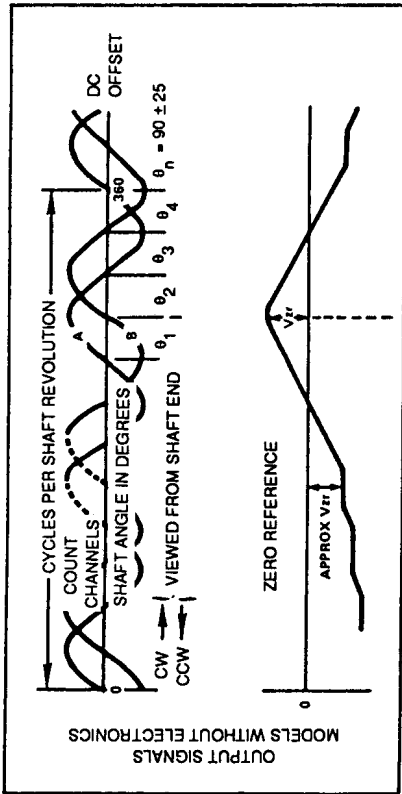


Figure 5-1. Silicon Cell Output

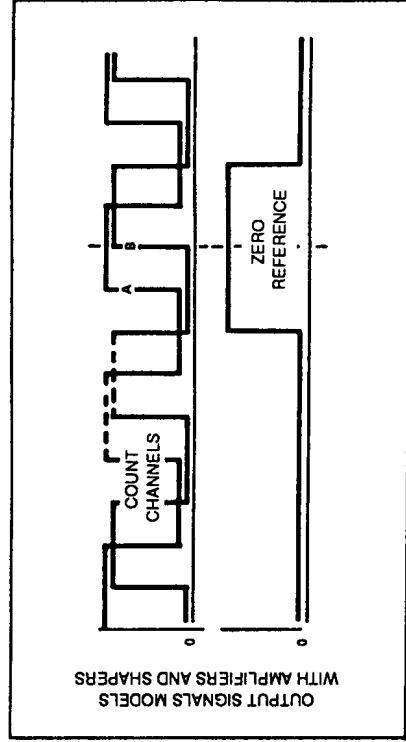


Figure 5-2. Shaped Output

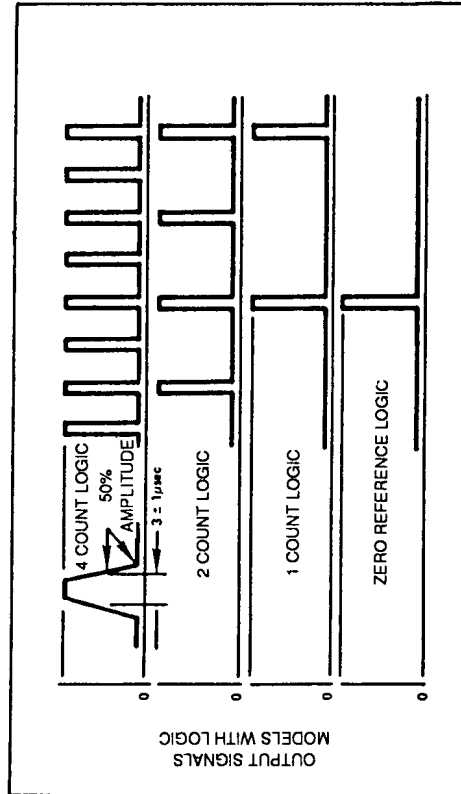


Figure 5-3. Pulse Output

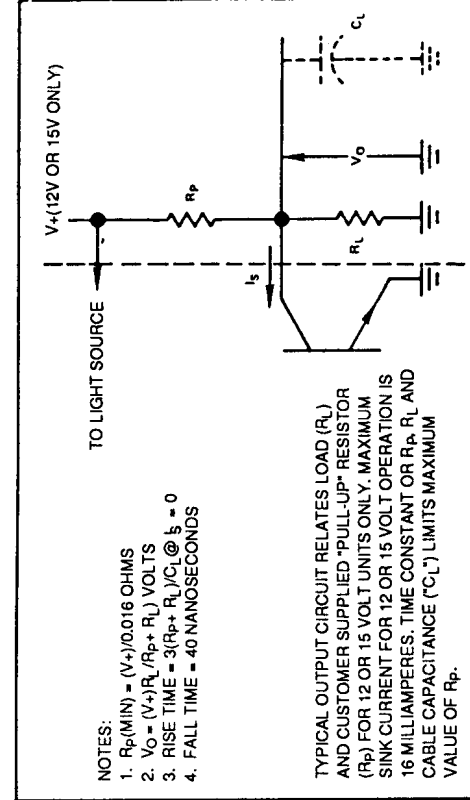


Figure 5-4. High Level Output

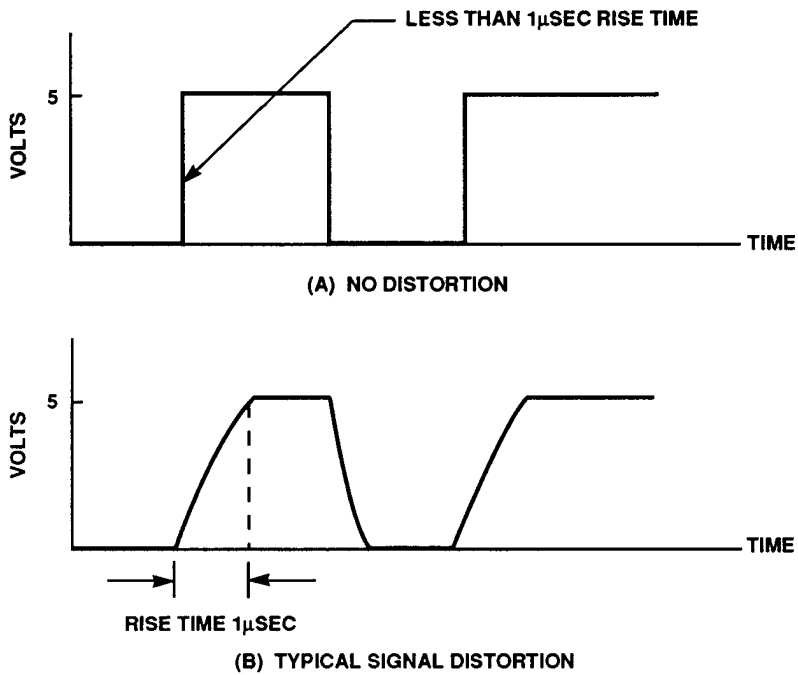


Figure 5-5. Signal Distortion

Table 5-1. Required Signal Conditioning vs. Cable Length

Waveform	Maximum Transmission Ft.	Reshaping Required
Sinewave	<5'	NR
TTL Squarewave (single ended)	<30'	>30'
TTL Squarewave (complementary)	<50'	>50'
TTL Squarewave (open collector)	same as TTL complementary except greater noise immunity	
Line Driver (differential)	>50'	NR
Amplified Analog (complementary)	<30'	>30'
Pulse	<20'	Not Feasible

The primary cause of the distortion is cable length or more specifically cable capacitance. To minimize distortion, high quality cable with capacitance less than 40 picofarads per foot should be used. The longer the cable, the greater the distortion. Beyond some cable length the signal must be reshaped before it can be used reliably. Assuming good quality cable is used, Table 5-1 gives rough breakpoints at which additional processing is required.

No reshaping is required for the sinewave output since the primary receiver must, by definition, be a signal shaper. The major problem with transmission of low level signals is electrical noise. Severity of the problem increases with transmission distance.

Squarewave distortion is not usually significant for transmission lengths less than 30 feet. Beyond 30 feet, some form of reshaping is required. Between 30 and 80 feet acceptable reshaping can generally be achieved with a differential line receiver or a comparator with hysteresis. These require that the complement of each of the encoder output waveforms be supplied to the input of the receiver (see Figure 5-6).

With squarewave output and cable lengths beyond 80 feet a differential line driver should be used at the encoder end and a differential line receiver at the destination.

Pulse output is not recommended for transmission greater than 10 feet. Pulse width is critical and accurate reshaping is not generally feasible.

Frequency response of the electronics can also distort the signal as illustrated in Figure 5-9. DRC encoders can typically be operated between 50 KHz and 200 KHz, depending on the type of encoder, without phase error being introduced. This phase error is a result of amplitude changes in the output with respect to the input.

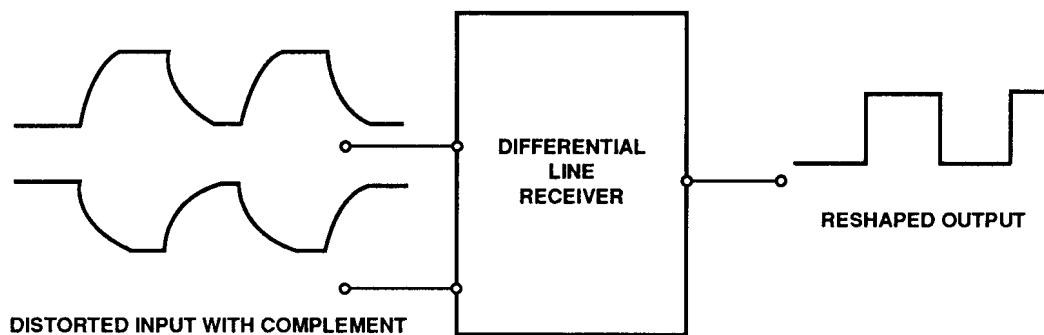


Figure 5-6. Reshaping with the Differential Line Receiver

Electrical Noise

The problem of radiated electrical noise, while potentially serious, can generally be overcome with a few simple precautions. Signal cables should always be run in trays isolated from other AC carriers and where possible, kept from the vicinity of noise generators such as electric welders and large AC motors.

When it is known that the cable will be exposed to noise, twisted wire pairs, individually shielded with an overall shield should be used. The shield should be tied to earth ground through the instrument case of the signal destination (see Figure 5-7). In severely noisy environments it may be necessary to also tie the signal ground to the instrument case through a 0.1 microfarad capacitor.

In addition to radiated noise, encoder operation may be influenced by transients in the encoders power supply. DRC encoders typically operate on 5 vdc $\pm 5\%$. Several varieties use internal voltage regulators or other voltage controlling components that allow higher input voltages to be used. However, line variations are a problem and line regulating is required for best results. Unregulated lines may introduce noise spikes into the encoder which can damage both the light source and encoder electronics. Conversely, insufficient power may cause the encoder to operate improperly. This is a common concern when long transmission distances are involved and the power supply is located at the destination of the encoder output. This situation can be controlled by utilizing a remote sense power supply which will maintain proper power levels.

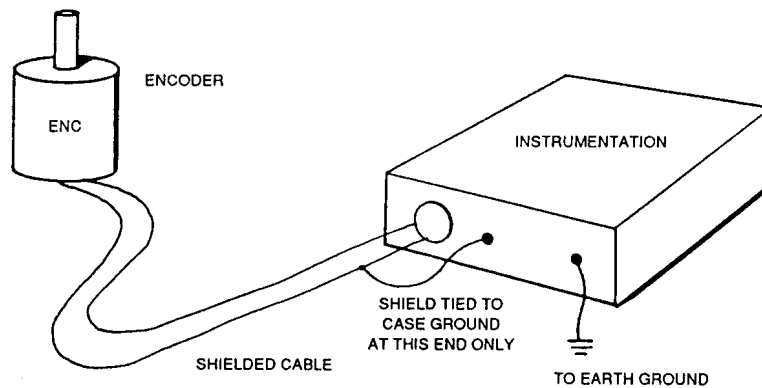


Figure 5-7. Recommended Cable Shield Grounding

MECHANICAL INTERFACE

The primary mechanical interface concerns that influence encoder accuracy and life are the encoder mount and the mechanical coupling. The encoder mount entails the aligning and securing of the encoder to the encoder mounting surface.

Alignment is guided using concentricity and perpendicular to the center of rotation, usually the encoder shaft which can be either a female or male type. The tolerances which must be used are generally dictated by the encoder type. Although, best results are achieved when tolerances are kept to a minimum, regardless of what type is used. Mounting tolerances may become tighter as the performance characteristics enhance. A pilot circle is usually provided on the encoder housing which when utilized will automatically concentrically align the encoder shaft to the center of the encoder mounting surface pilot interface circle. All bolt circle mounting patterns are concentric to the center of rotation as well. Encoder mounting faces are always perpendicular to the center of rotation. Securing the encoder can be done by using either a bolt circle pattern provided on the encoder mounting face or by using servo clips for a synchro mount. The latter allows the encoder to be rotated and adjusted to user preferred encoder body orientation.

The primary objective of the coupling is to accurately transmit the input motion to the encoder without subjecting the shaft to excessive loads (as specified for each product). Excess loads will damage the shaft bearings inducing premature bearing failure as well as increased potential for introducing encoder error. In addition to static loads, care must be taken to ensure that momentary or shock loads do not exceed specifications.

The most common methods of coupling the mechanical input motion to the rotary encoder are

- flexible coupling
- rack and pinion gearing
- gear-to-gear
- toothed belts

The flexible coupling (see Figure 5-8) is the most tolerant to misalignment and is the most accurate for transmission of mechanical input. Both these attributes make the flexible coupling the most commonly used.

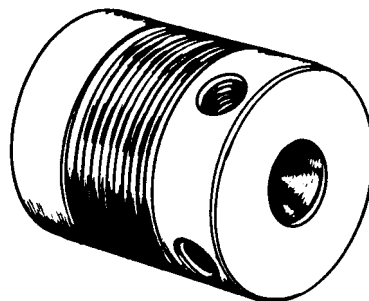


Figure 5-8. Relative Cost of Linear Encoder vs. Rotary with Rack and Pinion

ENCODER LIFE

Encoder life is most often limited due to

- optical failure
- shaft and bearing failure
- electronics failure

The predominant optical failure is premature degradation, either partial or complete, of the light source. The typical life of an LED operated at 5.0 volts is 100,000 hours compared to 40,000 hours for a lamp device. DRC encoders typically operate at 5 vdc $\pm 5\%$. Supply voltages must be regulated at either the power supply or in the encoder. When supply voltage drops below prescribed levels the output is insufficient to drive the electronics. Conversely, when the voltage is too high the life expectancy of the LED is significantly shortened. Reverse voltages can lead to an immediate loss of the device. Although the output of a lamp is greater than that of an LED, DRC believes that longer life and enhanced durability more than offset the loss of output.

Other optical failures result from deviations of LED output intensity at the photoreceptors due to misalignment and unclean or damaged optical components.

Shaft and bearing encoders are designed to have various life expectancies based on radial and axial loading, speed, and acceleration. Specified tolerances need to be adhered to in order to meet stated life expectancies. In many cases, shaft and bearing life can be enhanced by using less of the specified tolerances that are allowed.

Natural failure of encoder electronics is rare and a small factor in encoder life. In fact, improper repair or installation accounts for the vast majority of electronic failure. Careful adherence to DRC installation instructions and involvement of DRC technical assistance before troubleshooting will minimize electrical failure risk.

ERROR

In any closed loop system, there exists some degree of error which can be attributed to the encoder and some to the interaction of the encoder with the rest of the system.

Encoder error consists of quantization error, instrument error, and cycle interpolation error, as described in Chapter 3. Encoder error is largely determined by manufacturing and material tolerances inherent to each specific type. These types of error are relatively easy to identify and to quantify.

Total error is a combination of encoder error and error which is resultant of the interaction of the encoder with the system. System related errors typically are difficult to pinpoint and quantify.

Table 5-2 is a summary of the most frequently encountered sources of error.

Table 5-2. Potential Sources of Error

1. Manufacturing and Material Tolerances
2. Silicon Cell Characteristics
3. Scale or Disc Alignment
4. Regulation of Power Supply
5. Electrical Noise
6. Temperature Variation
7. Mechanical Coupling
8. Mechanical Vibration

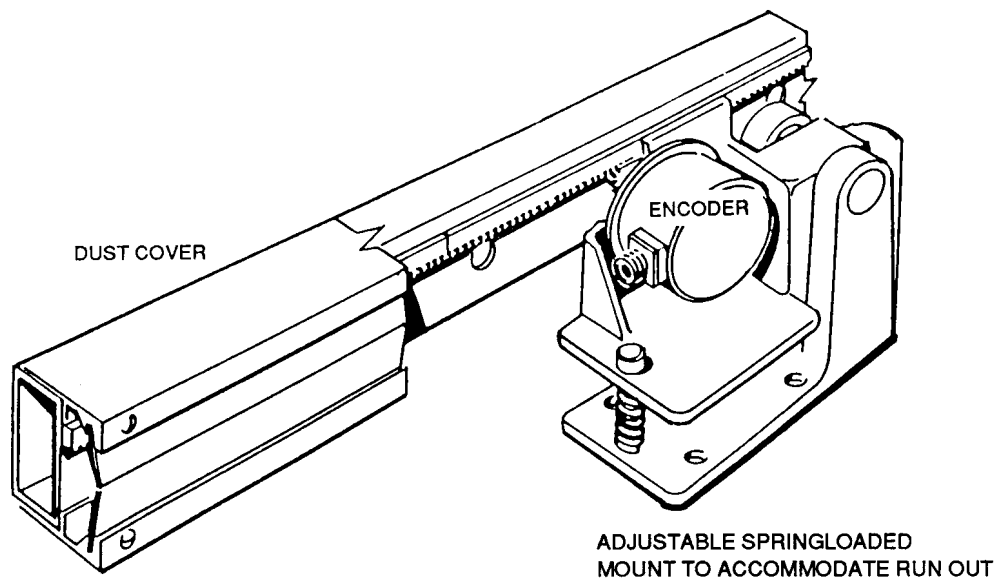


Figure 5-9. Rack and Pinion Spar Assembly

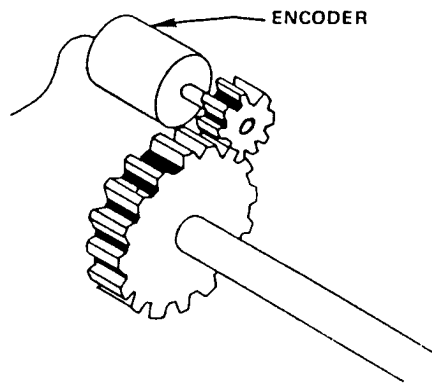


Figure 5-10. Gear-to-Gear Assembly

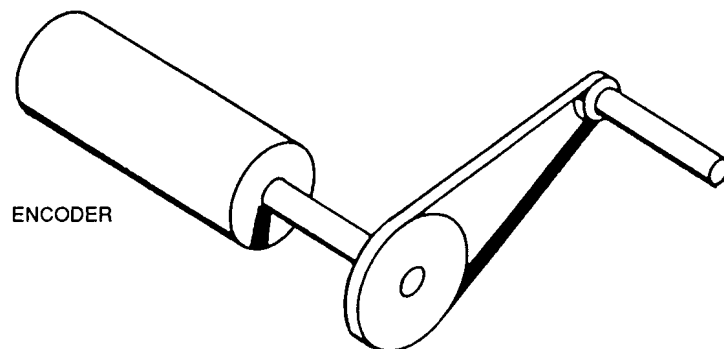


Figure 5-11. Precision Belt Drive

When the rack and pinion is used the encoder should be flexibly mounted to accommodate run out (see Figure 5-9). The rack must also be protected from foreign objects such as metal chips that could subject the encoder shaft to a shock load.

Gear-to-gear interfaces, similar to the rack and pinion, must- be carefully aligned to avoid bottoming the gears or subjecting the encoder shaft to stress due to momentary run out (see Figure 5-10).

Toothed belts are sometimes used but are not recommended because belt whip can subject the encoder shaft to shock loads and belt drives are relatively inaccurate (see Figure 5-11).

Linear encoders come in two basic designs. Enclosed, which indicates that the scale assembly and reading head assembly are factory aligned with the scale or grating enclosed and protected in a housing with mounting holes. The open linear, comprised of a reading head assembly and a scale that is not housed or protected from the environment with the alignment of two assemblies occurring at the application.

The accuracy of a linear encoder system largely depends on how well it is mounted. Although enclosed types are typically easier to mount than open types (by virtue of the factory prealigned condition), the installers ability to maintain all mounting parameters within specified tolerances is vital for proper operation, regardless of type.

For either type, the critical alignment dimensions all reference the axis of travel. One of the component assemblies is mounted to a fixed position while the other is mounted to the moving section. For both types, the relationship of the reading head/ optic assemblies to the scale is critical and must be maintained along the whole axis of travel. Thus, mounting the two component assemblies parallel to the axis of travel for all planes within specified tolerances will yield best results.

Greater care is required to mount the unenclosed system. Figure 5-12 illustrates the surfaces that must be aligned and used as referents for critical dimensions. The scale is mounted on surface "C". The readhead travels on surfaces "A" and "B". To maintain the fixed gap between the reticle and scale, surfaces "B" and "C" must be held parallel, and surface "A" must be perpendicular to "B". Surface "D" is the top edge of the scale. Parallelism between surfaces "D" and "A" is required to maintain parallelism between the reticles lines and those on the scale. If the lines are not parallel the light shutter will not properly modulate the light as was illustrated in Section 4. Alignment specifications depend on the particular encoder model and are provided with installation literature.

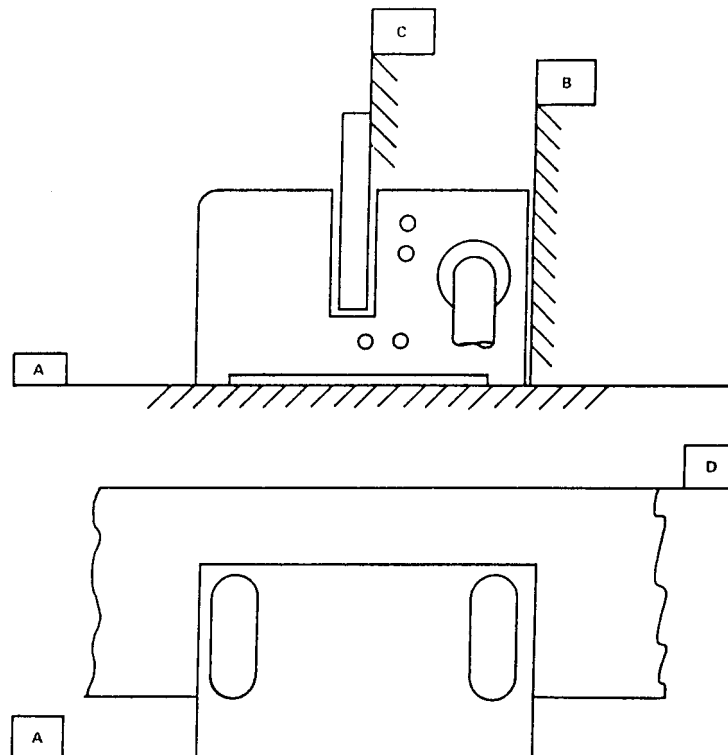


Figure 5-12. Scale and Encoder Mounting Requirements

Items 1, 2, and 3 are sources of encoder error. In preassembled factory aligned encoders, these errors are controlled by the manufacturer. In user assembled encoders care must be taken to maintain alignment within specified tolerances in order to ensure reliable feedback.

In some cases the magnitude of the encoder error caused by misalignment is predictable. For example, bending of the linear scale, as illustrated in Figure 5-13, introduces an error proportional to the displacement, “d”. When “d” is small relative to S (i. e., $2d/S - \sin 2d/S$). The concave surface of the scale is shortened by δ and the convex surface is lengthened by δ , where $\delta = 4td/ S$.

For

$$S = 12$$

$$T = \frac{1}{4}$$

$$D = 0.0012$$

$$\delta = \frac{4 \times \frac{1}{4} \times 0.0012}{12} = 0.0001 \text{ inch}$$

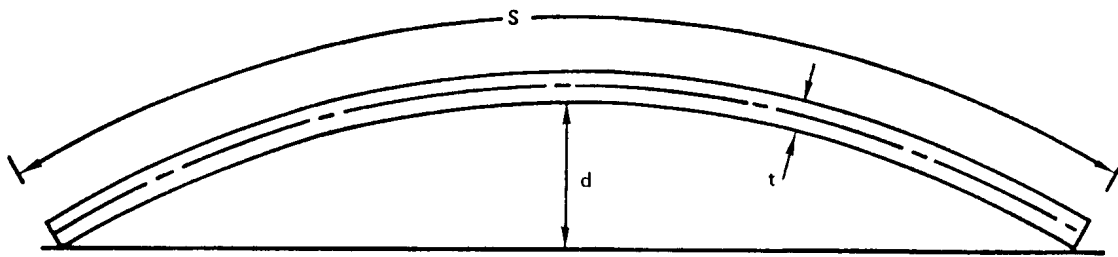


Figure 5-13. Scale Bending Error

In this example, when the lines are on the convex side of the bow, the encoder error will be +0.0001 inch per foot. When the lines are on the concave side the error will be -0.0001 inch per foot.

The requirements for power supply regulation and protection from electrical noise were discussed earlier. As stated, unregulated power supplies can damage encoder electronics or cause intermittent problems that are difficult to trace. Likewise, the error that is caused by electrical noise is random and the source is usually difficult to isolate.

Temperature influences encoder accuracy in several ways. The light source, if an LED, is very temperature sensitive as noted in Section 4. Changes in LED output levels may cause shifts in the encoder signals. Dimensional changes due to temperature fluctuations are most significant in linear glass scales. The coefficient of expansion for the type used in DRC transducers is 4.5×10^{-6} in./in. °F. The error resulting from a ± 300 °F temperature variation is ± 0.0016 in./ft.

The mechanical coupling selection should be made based on characteristics of the encoder relative to the application interface that will best transmit the mechanical input. Consideration should be made with respect to axial and radial loading, acceleration, velocity, vibration, accuracy, and resolution. Improper coupling can lead to error as well as encoder life limiting conditions.

6. APPLICATIONS

Thus far, this text has discussed encoder operation principles, various forms of feedback devices, and interfacing considerations. This chapter will highlight common formulas used to determine critical encoder performance characteristics. Also, we will examine various actual applications with regards to encoder specifying for performance and reliability.

SOME FORMULAS COMMON TO ENCODER USE

The following simple formulas are used to determine resolution, maximum frequency response, and maximum RPM. The results of these formulas, when applied with other encoder requirements, will help specify the encoder most suited for a particular application.

1. To determine required linecount of encoder when desired resolution is known.

Rotary: $360 / \text{desired resolution in degrees} = \text{counts per revolution}$

Example: $360 / .01 \text{ degrees} = 36,000 \text{ counts per revolution}$

2. To determine either maximum RPM, or maximum linecount, or maximum frequency response when two of the values are known.

Rotary: $(\text{RPM}/60) * \text{linecount} = \text{maximum frequency response}$

$(\text{Frequency response} * 60) / \text{linecount} = \text{maximum RPM}$

$(\text{Frequency response} * 60) / \text{RPM} = \text{maximum linecount}$

Example: $\frac{100 \text{ KHz} * 60}{2500 \text{ lc}} = 2400 \text{ RPM}$

Maximum frequency response of encoder = 100 KHz

Resolution requirement of encoder = 2500 cycles per revolution

Maximum encoder rotational speed = 2400 RPMs

Linear: $\frac{\text{Travel per minute}}{60} * \text{counts/ in. or mm.} = \text{max. frequency response}$

$\frac{\text{Frequency response} * 60}{\text{counts per in. or mm.}} = \text{travel per minute}$

$\frac{\text{Frequency response} * 60}{\text{travel per minute}} = \text{counts per in. or mm.}$

Example: $\frac{100 \text{ tpm}}{60} * 20,000 \text{ cpi} = 33.33 \text{ KHz}$

A linear application where displacement is 100 inches per minute and the encoder produces 20,000 counts per inch, then the maximum frequency response is 33.33 cycles per second (KHz).

3. To determine the linecount of a rotary encoder used in conjunction with a lead screw.

First: Determine the linear displacement of the screw (pitch).

$1 / \text{pitch} = \text{linear displacement of one revolution}$

Second: Determine desired system resolution.

i.e., 0.001, 0.0005, 0.00004, etc ...

Lastly: Apply the formula

$\text{Linear displacement} / \text{system resolution} = \text{counts per revolution}$

Example: Screw pitch is 10

System resolution is 0.000 1"

Linear displacement = 0. 1" per revolution

$0. 1 / 0.000 1 = 1000 \text{ counts per revolution}$

MACHINE TOOL

The machine tool industry is one of the largest markets for encoders. The typical machine requires positional control of work tables and spindles (X, Y, Z axis control). Velocity is controlled, as well. The type of position control system selected is dependent on the final operating specifications of the machine. The specifications most effected by the encoder feedback are resolution, accuracy, and repeat ability. As a rule, engineers will require that a linear encoder or a rotary encoder in conjunction with the lead screw, has a resolution that is a factor of 10 better than their specified machine resolution. For example, if the machine was specified as having a resolution of .001", then the encoder or encoder/ screw must have a resolution of .0001".

Accuracy is usually specified as a maximum deviation possible from the ideal position per inch. For example, a manufacturer may state that machine accuracy is .0001" per inch. That is, every successive inch of movement can deviate from the previous inch by not more than .0001". This type of error, called slope error, cumulates as length grows. Therefore, it is possible to deviate significantly over the entire length of travel. Manufacturers can compensate for slope error by utilizing error compensation programs available in many control packages. Linear encoders can be manufactured with minimal slope error. Calibration certificates that profiles the slope error come with these encoders from several manufacturers. Common accuracy grades are $\pm 5 \mu\text{m}$'s or $\pm 10 \mu\text{m}$'s over the entire length of the encoder. The encoder is only one component which contributes error to the system. Generally, the highest accuracy available is the most desirable. However, there is a cost trade-off that should be considered. Machines that specify at accuracy's down to .001" can use a "B" grade ($\pm 10 \mu\text{m}$'s) and save money, Machines specifying .0001" or better should use "A" grade ($\pm 5 \mu\text{m}$'s) only.

Repeatability may be the most crucial characteristic of the machine. Basically, repeatability is the machines capability to return to the same spot after a change of direction, utilizing the same amount of counts. Machines that use linear encoders rely solely on the encoders ability to repeat, whereas machines that use rotary encoders rely on the encoder in conjunction with the screw and coupling. Ball bearing riding readheads in linear encoders can have backlash (term indicating loss of motion after a change of direction) of less than 1 μm . A rotary encoder and ground ball screw system with quality components can achieve down to 1 μm , as well.

Selecting the best feedback device requires thorough evaluations of the entire application. Rotary and linear encoders can readily provide the resolution required. Accuracy is a function of many conditions outside the encoder. System orthogonality, temperature variations, and lead screw/ coupling translation are major factors involving system accuracy. Cost goes up as resolution and accuracy becomes finer. Length of travel impacts cost and accuracy.

Linears are generally considered more accurate because they are mounted directly to the work table, thus avoiding errors generated by coupling several mechanical components together.

Environmentally, conditions around a machine tool can frequently be adverse to encoders. Rotary encoders are sealed better than linear encoders. Linear encoders generally require more care when mounting and protection from environmental contaminants.

Cost evaluation must be considered from a system viewpoint. Components which play a role in this system are the encoder, screws (ground or ball), tables, motors, controls, and couplings.

Recommended DRC encoders for these type applications include

Rotary Models - 25, H25, HD2

Features: High frequency response, 40 lb. or greater shaft loading, Nema 13 enclosures, up to 60,000 PPR, zero reference, multiple output types, mechanically adaptable

Linear Models - LB, LX, LT, LH

Features: 0 - 72" length choice, up to .001 mm/.00005 in. directly from encoder, multiple selectable zero reference locations, less than .001 mm backlash, multiple accuracy grades, mismounting up to .012"

POSITIONING TABLES AND X, Y STAGES

Positioning tables and X, Y stages are mechanical structures that function as controlled moving platforms. Typically multi-axis, they are constructed of precision mechanical components providing orthogonal actuation. Orthogonal actuation refers to the stage's ability to maintain parallelism and perpendicularity relative to the axis of motion, over the entire travel length. Virtually any application where precisely controlled movement is required utilize some form of positioning table. Common applications include metrology equipment, microscopes, semiconductor transports, pick and place machines, gauging equipment, machine tools, and many forms of automated assembly equipment.

Lead screws are most commonly used as the drive mechanisms. These can be either manually or motor driven. In a manual system, table movement occurs as the operator turns the handle of a dial indicator directly coupled to the lead screw. Positional displacement is read directly off the dial indicator. Digital readout displays can be used by mounting an encoder either directly to the lead screw (rotary type) or to the table itself (linear type).

Motorized stages combine a motor for drive and an encoder with a readout for closed loop positional feedback. Often, stepper motors are used for drive and open loop positional feedback. Open loop is preferable when the application does not require great positional accuracy, high resolution or repeatability ensured by using an encoder. When a closed loop system is preferable, the least expensive encoder to use is a modular kit type which mounts directly to the motor shaft or lead screw. This type device requires the alignment of the encoder by the stage manufacturer. Recently, the designs of this type encoder has progressed to the point where the gapping and centering alignments are performed at the encoder manufacturers. The stage manufacturers need only slide the encoder on and secure it. This type encoder requires the motor shaft to have limited TIR and axial growth because the encoder utilizes the motor shaft to maintain proper alignments. Too much TIR and shaft growth will cause the encoder signals to become unstable as optimal alignment is lost. When this condition exists, using an encoder with an integral coupling and shaft assembly is preferable. The flexible coupling absorbs motor shaft TIR and growth so the encoder continues to operate properly. This type unit is environmentally sealed better and more durable, as well.

If the stage application requires greater positional accuracy, mounting a linear encoder directly on the table eliminates certain types of error intrinsic to rotational encoder systems (ball screw, coupling, and encoder), when installed correctly. Linear encoders and their inherent characteristics are discussed in detail later on in this chapter.

Recommended DRC encoders for these type applications include

Rotary Models - C152, C25

Features: Integral shaft coupling with bell housing, multiple output stages, resolutions to 60,000 counts per revolution, various output termination types, zero reference, easy installation

Modular Models - TK730, TK731, TK830, T23

Features: Easy installation, resolutions to 10, 160 counts per revolution, zero reference, 200 KHz frequency operation, analog or digital signals

Linear Models - LB, LX, LT, LH (*Enclosed*)

Linear Models - SRL, LK, OLK (*Open*)

Features: Up to 72' of measuring length, resolutions to 1 micron, different accuracy grades, analog or digital signals, generous mounting tolerances

PHOTO PLOTTERS

Photo plotters, essentially programmable X, Y printers, are used for design and illustration. Through precision placement of pixels, designers can virtually create photograph quality prints. Designs can be resolution enhanced, enlarged or contracted to scale, color highlighted or accentuated.

There are two basic types of plotters, bed and drum. The bed type incorporates a gantry system to position the printer head on the X and Y axis above an adjustable sloping bed. Linear encoders mounted to the X and Y axis stages provide displacement feedback in order to accurately locate the printer head with re-

spect to the bed. Linear encoders are preferable for this application because they are highly accurate and mechanically fit well onto the moving stages.

The drum type utilizes a linear encoder for X axis control and a high resolution rotary encoder for the rotating drum to precisely locate the printhead. The rotary encoder is rotating synchronous with the drum and is used as a master clock to control rotational speed precisely. This type of system requires high resolution from the encoders that are submicron for the linear and down to several arc seconds for the rotary.

Recommended DRC encoders for this type application include

Linear Models - LB, LX

Rotary Models - M35, M25 (*high resolution*)

METROLOGY

Manufacturers of metrology equipment require closed loop position feedback as a matter of basic design. Typical position sensing systems include lasers, optical encoders, and magnetic encoders. Linear types are used on X, Y, and Z axis while rotary types are used on θ (theta) axis.

The position feedback system is a vital component in any device that is used as a measurement tool. Coordinate measuring machines, optical comparators, and microscopes are common examples of this type equipment.

Critical characteristics that the position feedback system must have include high accuracy, high resolution, and high repeatability. Other important considerations include length, installation ease, output capabilities, and cost.

DRC linear encoders are frequently used in these applications. In applications where accuracy, repeatability, and resolution must be high performance, DRC offers multiple types of open and enclosed linear devices which provide these performance characteristics. The advantage of linear encoders is the direct linear positional feedback without the mechanical errors that can be induced from rotary encoders coupled to leadscrews. Linear enclosed varieties include the models LB and LX. Repeatability can be less than 1 micron, resolutions down to 1/10th micron and slope accuracy down to 3 microns over the entire travel length.

Open linear encoders are often preferred. These are available in either contacting or non-contacting configurations. The contacting encoders include the models SRL and LK. These units have small cross sections and can provide the same performance characteristics as the enclosed types. The OLK is a non-contacting device which can be used for applications where higher speed and zero backlash is required. Generally, open type linear encoders are more difficult to mount than enclosed varieties, but are less expensive, as well.

Recommended DRC encoders for this type application include

Linear Models - LB, LX (*Enclosed*)

Linear Models - LK, SRL, OLK, L50 (*Open*)

7. REFERENCE

SI UNITS AND SYMBOLS

The SI system consists of six base units, two supplementary units, a series of derived units consistent with the base and supplementary units, and a series of approved prefixes for the formation of multiples and submultiples of the various units.

Table 7-1A. SI Units

<i>Quantity</i>	<i>Unit</i>	<i>SI Symbol</i>	<i>Formula</i>
<i>Base Units:</i>			
length	meter	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
luminous intensity	candela	cd	...
plane angle	radian	rad	...
solid angle	steradian	sr	...
<i>Derived Units:</i>			
acceleration	meter per second squared	...	m/s^2
activity (of a radioactive source)	disintegration per second	...	(disintegration/s)
angular acceleration	radian per second squared	...	rad/s^2
angular velocity	radian per second	...	rad/s
area	square meter	...	m^2
density	kilogram per cubic meter	...	kg/m^3
electric capacitance	farad	F	$A \cdot s / V$
electric field strength	volt per meter	...	V/m
electric inductance	henry	H	$V \cdot s / A$
electric potential difference	volt	V	W/A
electric resistance	ohm	Ω	V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	$kg \cdot m / s^2$
frequency	hertz	Hz	(cycle)/s
illumination	lux	lx	lm/m^2
luminance	candela per square meter	...	cd / m^2
luminous flux	lumen	lm	$cd \cdot sr$
magnetic field strength	ampere per meter	...	A/m
magnetic flux	weber	Wb	$V \cdot s$
magnetic flux density	tesla	T	Wb/m^2
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	newton per square meter	...	N/m^2
quantity of electricity	coulomb	C	$A \cdot s$
quantity of heat	joule	J	$N \cdot m$

Table 7-1A. SI Units (Cont.)

<i>Quantity</i>	<i>Unit</i>	<i>SI Symbol</i>	<i>Formula</i>
radiant intensity	watt per steradian	...	W/sr

specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	newton per square meter	...	N/m ²
thermal conductivity	watt per meter-kelvin	...	W/m·K
velocity	meter per second	...	m/s
viscosity, dynamic	newton-second per square meter	...	N·s/m ²
viscosity, kinematic	square meter per second	...	m ² /s
voltage	volt	V	W/A
volume	cubic meter	...	m ³
wavenumber	reciprocal meter	...	(wave)/m
work	joule	J	N·m

*The International System of Units was adopted by thirty-six nations, including the U.S., at the 11th General Conference on Weights and Measures in 1960.

Table 7-1 B. Multiple and Submultiple Units

<i>Multiplication Factors</i>	<i>Prefix</i>	<i>SI Symbol</i>
1 000 000 000 000 = 10 ¹²	tera	T
1 000 000 000 = 10 ⁹	giga	G
1 000 000 = 10 ⁶	mega	M
1 000 = 10 ³	kilo	k
100 = 10 ²	hecto	h
10 = 10 ¹	deka	da
0.1 = 10 ⁻¹	deci	d
0.01 = 10 ⁻²	centi	c
0.001 = 10 ⁻³	milli	m
0.000 001 = 10 ⁻⁶	micro	:
0.000 000 001 = 10 ⁻⁹	nano	n
0.000 000 000 001 = 10 ⁻¹²	pico	p
0.000 000 000 000 001 = 10 ⁻¹⁵	fernto	f
0.000 000 000 000 000 001 = 10 ⁻¹⁸	atto	a

Table 7-2. Definition of Basic SI Units

<i>Unit</i>	<i>Definition</i>
meter	The meter is the length equal to 1650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels 2p ₁₀ and 5d ₅ of the krypton-86 atom.
kilogram	The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.
second	The second is the duration of 9 192 631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
ampere	The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible cross section, and placed one meter apart in vacuum, would produce between these conductors a force equal to 2 × 10 newton per meter of length.
kelvin	The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
candela	The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/ 600 000 square meter of a blackbody at the temperature of freezing platinum under a pressure of 101 325 newtons per square meter.

radian	The unit of measure of a plane angle with its vertex at the center of a circle and subtended by an arc equal in length to the radius.
steradian	The unit of measure of a solid angle with its vertex at the center of a sphere and enclosing an area of the spherical surface equal to that of a square with sides equal in length to the radius.

Table 7-3. Definitions of Derived Units of the International System Having Special Names

<i>Physical Quantity</i>	<i>Unit and Definition</i>
electric capacitance	The <i>farad</i> is the capacitance of a capacitor between the plates of which there appears a difference of potential of one volt when it is charged by a quantity of electricity equal to one coulomb.
electric inductance	The <i>henry</i> is the inductance of a closed circuit in which an electromotive force of one volt is produced when the electric current in the circuit varies uniformly at a rate of one ampere per second.
electric potential difference (electromotive force)	The <i>volt</i> (unit of electric potential difference and electromotive force) is the difference of electric potential between two points of a conductor carrying a constant current of one ampere, when the power dissipated between these points is equal to one watt.
electric resistance	The <i>ohm</i> is the electric resistance between two points of a conductor when a constant difference of potential of one volt, applied between these two points, produces in this conductor a current of one ampere, this conductor not being the source of any electromotive force.
energy	The <i>joule</i> is the work done when the point of application of a force of one newton is displaced a distance of one meter in the direction of the force.
force	The <i>newton</i> is that force which, when applied to a body having a mass of one kilogram gives it an acceleration of one meter per second per second.
frequency	The <i>hertz</i> is a frequency of one cycle per second.
illumination	The <i>lux</i> is the luminous intensity given by a luminous flux of one lumen per square meter.
luminous flux	The <i>lumen</i> is the luminous flux emitted in a solid angle of one steradian by a point source having a uniform intensity of one candela.
magnetic flux	The <i>weber</i> is the magnetic flux which, linking a circuit of one turn, produces in it an electromotive force of one volt as it is reduced to zero at a uniform rate in one second.
magnetic flux density	The <i>tesla</i> is the magnetic flux density given by a magnetic flux of one weber per square meter.
power	The <i>watt</i> is the power which gives rise to the production of energy at the rate of one joule per second.
quantity of electricity	The <i>coulomb</i> is the quantity of electricity transported in one second by a current of one ampere.

Table 7-4. Conversion Factors for Physical Quantities

*Alphabetical List of Units
(Symbols of SI Units given in parentheses)*

<i>To Convert From</i>	<i>To</i>	<i>Multiply by</i>
------------------------	-----------	--------------------

abampere	ampere (A)	1.000	000	E+01
abcoulomb (C)	coulomb (C)	1.000	000	E+01
abfarad	farad (F)	1.000	000	E + 09
abhenry	henry (H)	1.000	000	E - 09
abmho	mho	1.000	000	E + 09
abohm	ohm (Ω)	1.000	000	E - 09
abvolt	volt (V)	1.000	000	E - 08
acre	meter ² (M ²)	4.046	856	E + 03
ampere (international of 1948)	ampere (A)	9.998	35	E - 01
angstrom	meter (m)	1.000	000	E - 10
astronomical unit	meter (m)	1.495	98	E + 11
atmosphere (normal)	newton/ meter ² (N/m ²)	1.013	250	E + 05
atmosphere (technical = 1 kgf/CM2)	newton/ meter ² (N/m ²)	9.806	650	E + 04
bar	newton/ meter ² (N/m ²)	1.000	000	E + 05
barn	meter ² (m ²)	1.000	000	E - 28
barrel (for petroleum, 42 gal)	meter ³ (m ³)	1.589	873	E - 01
British thermal unit (international table)	joule (J)	1.055	056	E + 03
British thermal unit (thermochemical)	joule (J)	1.055	87	E + 03
British thermal unit (mean)	joule (J)	1.054	350	E + 03
British thermal unit (39 F)	joule (J)	.059	67	E + 03
British thermal unit (60 F)	joule (J)	1.054	68	E + 03
bushel (U.S.)	meter ³ (m ³)	3.523	907	E - 02
caliber	meter (m)	2.540	000	E - 04
calorie (international table)	joule (J)	4.186	800	E + 00
calorie (mean)	joule (J)	4.190	02	E + 00
calorie (thermochemical)	joule (J)	4.184	000	E + 00
calorie (15 C)	joule (J)	4.185	80	E + 00
calorie (20 C)	joule (J)	4.181	90	E + 00
calorie (kilogram, international table)	joule (J)	4.186	800	E + 03
calorie (kilogram, mean)	joule (J)	4.190	02	E + 03
calorie (kilogram, thermochemical)	joule (J)	4.184	000	E + 03
carat (metric)	kilogram (kg)	2.000	000	E - 04
centimeter of mercury (0 C)	newton/ meter ² (N/m ²)	1.333	22	E + 03
centimeter of water (4 C)	newton/ meter ² (N/m ²)	9.806	38	E+01
centipoise	newton-second/meter ² (N•s/m ²)	1.000	000	E - 03
circular mil	meter ² (m ²)	5.067	075	E - 10
clo	kelvin-meter ² /watt (K•m ² / W)	2.003	712	E-01
coulomb (international of 1948)	coulomb (C)	9.998	35	E-01
cup	meter ³ (m ³)	2.365	882	E - 04
curie	disintegration/ second	3.700	000	E+ 10
day (mean solar)	second (s)	8.640	000	E + 04
day (sidereal)	second (s)	8.616	409	E + 04
degree (angle)	radian (rad)	1.745	329	E - 02
Degree	kelvin (K)	$t_K = t_C + 273.15$		
degree Fahrenheit	degree Celsius	$t_C = (t_F - 32)/1.8$		
degree Fahrenheit	kelvin (K)	$t_K = (t_F + 459.67)/1.8$		
degree Rankine	kelvin (K)	$t_K = t_R / 1.8$		
decibar	newton/meter ²	1.000	000	E + 04
dyne	newton (N)	1.000	000	E - 05
electron volt	joule (J)	1.602	10	E - 19

Table 7-4. Conversion Factors for Physical Quantities (Cont.)

<i>To Convert From</i>	<i>To</i>	<i>Multiply by</i>		
EMU of capacitance	farad (F)	1.000	000	E + 09
EMU of current	ampere (A)	1.000	000	E+ 01
EMU of electric potential	volt (V)	1.000	000	E – 08
EMU of inductance	henry (H)	1.000	000	E – 09
EMU of resistance	ohm (Ω)	1.000	000	E – 09
ESU of capacitance	farad (F)	1.112	6	E – 12
ESU of current	ampere (A)	3.335	6	E – 10
ESU of electric potential	volt (V)	2.997	9	E + 02
ESU of	henry (H)	8.987	6	E + 11
ESU of	ohm (Ω)	8.987	6	E + 11
Erg	joule (J)	1.000	000	E – 07
farad (international of 1948)	farad (F)	9.995	05	E – 01
faraday (based on carbon-12)	coulomb (C)	9.648	70	E + 04
faraday (chemical)	coulomb (C)	9.649	57	E + 04
faraday (physical)	coulomb (C)	9.652	19	E + 04
fathom	meter (m)	1.828	800	E + 00
fermi (femtometer)	meter (m)	1.000	000	E - 15
fluid ounce (U.S.)	meter ³ (m ³)	2.957	353	E - 05
foot	meter (m)	3.048	000	E - 01
foot (U.S. survey)	meter (in)	3.048	006	E - 01
foot of water (39.2)	newton/meter ² (N/m ²)	2.988	98	E + 03
footcandle	lumen/meter ² (lm m ²)	1.076	391	E+01
footlambert	candela/meter ² (cd/m ²)	3.426	259	E + 00
gal (galileo)	meter/second ² (m/s ²)	1.000	000	E - 02
gallon (Canadian liquid)	meter ³ (m ³)	4.546	122	E - 03
gallon (U.K. liquid)	meter ³ (m ³)	4.546	087	E - 03
gallon (U.S. dry)	meter ³ (m ³)	4.404	884	E - 03
gallon (U.S. liquid)	meter ³ (m ³)	3.785	412	E - 03
gamma	tesla (T)	1.000	000	E - 09
gauss	tesla (T)	1.000	000	E - 04
gilbert	ampere-turn	7.957	747	E - 01
gill (U.K.)	meter ³ (m ³)	1.420	652	E - 04
gill (U.S.)	meter ³ (m ³)	1.182	941	E - 04
grad	degree (angular)	9.000	000	E-01
grad	radian (rad)	1.570	796	E - 02
grain (1/ 7000 lbm avoirdupois)	kilogram (kg)	6.479	891	E - 05
gram	kilogram (kg)	1.000	000	E - 03
henry (international of 1948)	henry (H)	1.000	495	E1 -00
horsepower (550 ft-lbs)	watt (W)	7.456	999	E1 -02
horsepower (boiler)	watt (W)	9.809	50	E1 –03
horsepower (electric)	watt (W)	7.460	000	E + 02
horsepower (metric)	watt (W)	7.354	99	E + 02
horsepower (water)	watt (W)	7.460	43	E + 02
horsepower (U.K.)	watt (W)	7.457	0	E + 02
hour (mean solar)	second (s)	3.600	000	E + 03
hour (sidereal)	second (s)	3.590	170	E + 03
hundredweight (long)	kilogram (kg)	5.080	235	E+01
hundredweight (short)	kilogram (kg)	4.535	924	E+01
inch	meter (m)	2.540	000	E – 02
inch of mercury (32 F)	newton/ meter ² (N/m ²)	3.386	389	E + 03
inch of mercury (60 F)	newton/meter ² (N/m ²)	3.376	85	E + 03
inch of water (39.2 F)	newton/meter ² (N/m ²)	2.490	82	E + 02
inch of water (60 F)	newton/ meter ² (N/m ²)	2.488	4	E + 02

Table 7-4. Conversion Factors for Physical Quantities (Cont.)

<i>To Convert From</i>	<i>To</i>	<i>Multiply by</i>		
joule (international of 1948)	joule (J)	1.000	165	E + 00
kayser	I / meter (I / m)	1.000	000	E + 02
kelvin	degree Celsius	t c =	t K -	273.15
kilocalorie (international table)	joule (J)	4.186	800	E + 03
kilocalorie (mean)	joule (J)	4.190	02	E + 03
kilocalorie (thermochemical)	joule (J)	4.184	000	E + 03
kilogram-force (kgf)	newton (N)	9.806	650	E + 00
kilogram-mass	kilogram (kg)	1.000	000	E + 00
kilopond-force	newton (N)	9.806	650	E + 00
kip	newton (N)	4.448	222	E + 03
knot (international)	meter/ second (m/s)	5.144	444	E-01
lambert	candela/ meter ² (cd /m ²)	I/π		E + 04
lambert	candela/ meter ² (cd /m ²)	3.183	099	E + 03
langley	joule/meter ² (J/m ²)	4.184	000	E + 04
light year	meter (m)	9.460	55	E + 15
liter	meter ³ (m ³)	1.000	000	E - 03
lux	lumen/ meter ² (lm/ m ²)	1.000	000	E + 00
maxwell	weber (Wb)	1.000	000	E - 08
micron	meter (m)	1.000	000	E - 06
mil	meter (m)	2.540	000	E - 05
mile (international nautical)	meter (m)	1.852	000	E + 03
mile (U.K. nautical)	meter (m)	1.853	184	E + 03
mile (U.S. nautical)	meter (m)	1.852	000	E + 03
mile (U.S. statute)	meter (m)	1.609	344	E + 03
millibar	newton/meter ² (N/m ²)	1.000	000	E + 02
millimeter of mercury (O C)	newton/ meter ² (N/ m ²)	1.333	224	E + 02
minute (angle)	radian (rad)	2.908	882	E - 04
minute (mean solar)	second (s)	6.000	000	E+01
minute (sidereal)	second (s)	5.983	617	E+01
moment of inertia (IbM.ft2)	kilogram-meter ² (kg-m ²)	4.214	012	E - 02
moment of inertia (Ibm-in2)	kilogram-meter ² (kg-m ²)	2.926	397	E - 05
moment of section (second moment of area) (foot4)	meter ⁴ (m ⁴)	8.630	975	E - 03
moment of section (second moment of area) (inch4)	meter ⁴ (M ⁴)	4.162	314	E - 07
month (mean calendar)	second (s)	2.628	000	E + 06
oersted	ampere/ meter (A/ in)	7.957	747	E+01
ohm (international of 1948)	ohm (Ω)	1.000	495	E + 00
ounce-force (avoirdupois)	newton (N)	2.780	139	E-01
ounce-mass (avoirdupois)	kilogram (kg)	2.834	952	E - 02
ounce-mass (troy or apothecary)	kilogram (kg)	3.110	348	E - 02
ounce (U.S. fluid)	meter ³ (m ³)	2.957	353	E - 05
parsec	meter (in)	3.083	74	E + 16
pascal	newton/ meter ² (N/m ²)	1.000	000	E + 00
peck (U.S.)	meter ³ (m ³)	8.809	768	E - 03
pennyweight	kilogram (kg)	1.555	174	E - 03
perm (O C)	kilogram/ newton-second (kg/ N•s)	5.721	35	E - 11
perm (23 C)	kilogram/ newton-second (kg/ N•s)	5.745	25	E - 11
perm-inch (O C)	kilogram-meter/ newton-second (kg•m/ N•s)	1.453	22	E - 12
perm-inch (23 C)	Kilogram-meter/ newton-second (kg•m/ N•s)	1.459	29	E - 12

Table 7-4. Conversion Factors for Physical Quantities (Cont.)

<i>To Convert From</i>	<i>To</i>	<i>Multiply by</i>		
phot	Lumen/meter ² (IM/ m ²)	1.000	000	E + 04
pica (printer's)	meter (m)meter ³ (m ³)	4.217	518	E -
pint (U.S. dry)	meter ³ (m ³)	035.506	105	E - 04
pint (U.S. liquid)	meter	4.731	765	E - 04
point (printer's)	newton-second/ meter ² (N-s/m ²)	3.514	598	E - 04
poise (absolute viscosity)	newton (N)	1.000	000	E-01
poundal	newton (N)	1.382	550	E - 01
pound-force (Ibf avoirdupois)	kilogram (kg)	4.448	222	E + 00
pound-mass (Ibm avoirdupois)	kilogram (kg)	4.535	924	E - 01
pound-mass (troy or apothecary)	meter ³ (m ³)	3.732	417	E - 0 1
quart (U.S. dry)	meter ³ (m ³)	1.101	221	E - 03
quart (U.S. liquid)	joule/ kilogram (J / kg)	9.463	529	E - 04
rad (radiation dose absorbed)	meter ² / newton-second (m ² / N•s)	1.000	000	E - 02
rhe	meter (in)	1.000	000	E+01
rod	coulomb/ kilogram (C/ kg)	5.029	200	E + 00
roentgen	radian (rad)	2.579	760	E - 04
second (angle)	second (s)	4.848	137	E - 06
second (sidereal)	meter ² (m ²)	9.972	696	E - 01
section	meter ³ (m ³)	2.589	988	E + 06
section modulus (foot ³)	meter ³ (m ³)	2.831	685	E - 02
section modulus (inch ³)	second (s)	1.638	706	E - 05
shake	kilogram (kg)	1.000	000	E - 08
slug	ampere (A)	1.459	390	E+01
statampere	coulomb (C)	3.335	640	E - 10
statcoulomb	farad (F)	3.335	640	E - 10
statfarad	henry (H)	1.112	650	E - 12
stathenry	mho ⁶	8.987	554	E+ 11
statmho	ohm (Ω)	1.112	650	E - 12
statohm	meter (m)	8.987	554	E + 11
statute mile(U.S.)	volt (V)	1.609	344	E + 03
statvolt	meter ³ (m ³)	2.997	925	E + 02
stere	candela / meter ² (cd /m ²)	1.000	000	E + 00
stilb	meter ² /second (m ² /S)	1.000	000	E + 04
stoke (kinematic viscosity)	meter ³ (m ³)	1.000	000	E - 04
tablespoon	meter ³ (m ³)	1.478	676	E - 05
teaspoon	kilogram/ meter (kg/ m)	4.928	922	E - 06
tex	kilogram (kg)	1.000	000	E - 06
ton (assay)	kilogram (kg)	2.916	667	E - 02
ton (long, 2240 lbm)	kilogram (kg)	1.016	047	E + 03
ton (metric)	joule (J)	1.000	000	E + 03
ton (nuclear equivalent of TNT)	meter ³ (m ³)	4.20		E + 09
ton (register)	kilogram (kg)	2.831	685	E + 00
ton (short, 2000 lbm)	kilogram (kg)	9.071	847	E + 02
tonne	newton/ meter ² (N/m ²)	1.000	000	E + 03
torr (mm Hg, 0 C)	meter ² (m ²)	1.333	22	E + 02
township	weber (Wb)	9.323	957	E + 07
unit pole	volt (absolute) (V)	1.256	637	E - 07
volt (international of 1948)	watt (W)	1.000	330	E + 00
watt (international of 1948)	meter (m)	1.000	165	E + 00
yard	second (s)	9.144	000	E-01
year (calendar)	second (s)	3.153	600	E + 07
year (sidereal)	second (s)	3.155	815	E + 07
year (tropical)	second (s)	3.155	693	E + 07

Table 7-5. Conversion Factors for Servo Calculations

<i>To Convert From</i>	<i>To</i>	<i>Multiply By</i>
<i>Length</i>		
inches	cm	2.540
feet	cm	30.48
cm	inches	0.3937
feet	inches	12.
cm	feet	3.281×10^{-2}
inches	feet	8.333×10^{-2}

Mass

oz	gm	28.35
lb	gm	453.6
slug	gm	1.459×10^4
gm	oz	3.527×10^{-2}
lb	oz	16.

Table 7-5. Conversion Factors for Servo Calculations (Cont.)

<i>To Convert From</i>	<i>TO</i>	<i>Multiply By</i>
<i>Mass</i>		
slug	oz	514.7
gm	lb	2.205×10^{-3}
oz	lb	6.250×10^{-2}
slug	lb	32.17
gm	slug	6.853×10^{-5}
oz	slug	1.943×10^{-3}
lb	slug	3.108×10^{-2}

*1 slug mass goes at 1 ft/sec² when acted upon by 1 lb force.

Force

gm*	dyne	980.7
oz	dyne	2.780×10^4
lb	dyne	4.448×10^5
dyne	gm*	1.020×10^{-3}
dyne	oz	3.597×10^{-5}
dyne	lb	2.248×10^{-6}

*Used as force units.

Torque

gm cm	dyne cm	980.7
oz in	dyne cm	7.062×10^4
lb ft	dyne cm	1.356×10^7

dyne cm	gm cm	1.020×10^{-3}
oz in	gm. cm	72.01
lb ft	gm cm	1.383×10^4
dyne cm	oz in	1.416×10^{-5}
gm cm	oz in	1.389×10^{-2}
lb ft	oz in	192.0
dyne cm	lb, ft	7.376×10^{-8}
gm cm	lb, ft	7.233×10^{-5}
oz in	lb, ft	5.208×10^{-3}

Torque to Inertia Ratio, or Acceleration at Stall. (Stall torque divided by rotor inertia.)

oz in/ gm CM2	rad/ seC ²	7.062×10^4
oz in/ oz in2	rad/seC ²	386.1

Rotation

rpm	degrees/sec:	6.
rad/sec	degrees/sec:	57.30
degrees/sec	rpm	0.1667
rad/sec	rpm	9.549

Table 7-5. Conversion Factors for Servo Calculations (Cont.)

<i>To Convert From</i>	<i>To</i>	<i>Multiply By</i>
<i>Length</i>		
degrees/sec	rad/sec:	1.745×10^{-2}
rpm	rad/sec	0.1047
<i>Moment of Inertia</i>		
oz in ²	gm cm ²	182.9
lb ft ²	gm cm ²	14.214×10^5
skyg ft ²	gm cm ²	1.356×10^7
gin CM ²	oz in ²	5.467×10^{-3}
lb ft ²	oz in ²	2.304×10^3
slug ft ²	oz in ²	7.412×10^4
gin cm ²	lb ft ²	2.373×10^{-6}
oz in ²	lb ft ²	4.340×10^{-4}
slug ft ²	lb ft ²	32.17
gm cm ²	slug ft ²	7.376×10^4
oz in ²	slug ft ²	1.349×10^{-5}
lb ft ²	slug ft ²	3.108×10^{-2}
in oz sec ²	oz in ²	3.86×10^2
oz in ²	in oz sec ²	2.58×10^{-3}
<i>Power</i>		
(oz in) (deg/sec)	h.p	1.653×10^{-7}
(oz in) (rpm)	h.p	9.917×10^{-7}
(lb ft) (deg/sec)	h.p	3.173×10^{-5}
(lb ft) (rpm)	h.p	1.904×10^{-4}
watts	h.p	1.341×10^{-3}
(oz in) (deg/sec)	watts	1.232×10^{-4}
(oz in) (rpm)	watts	7.395×10^{-4}
(lb ft) (deg/sec)	watts	2.366×10^{-2}
(lb ft) (rpm)	watts	0.1420
h.p.	watts	745.7
<i>Damping Coefficient of 2 Phase Motor.</i> (Stall torque divided by top motor speed.)		
oz in/rpm	lb ft/rad sec ⁻¹	4.974×10^{-2}
oz in/rpm	dyne cm/rad sec ⁻¹	6.743×10^5
<i>Time Constant of 2 Phase Motor.</i> (Rotor inertia divided by motor damping coefficient.)		
gm cm ² × rpm oz in	sec	1.483×10^{-6}
gm cm ² × rpm oz in	sec	2.712×10^{-4}
<i>Loop Gain</i> (Also called stiffness, sensitivity, torque gradient.)		
oz in/degree	lb ft/rad	0.2984
oz in/degree	dyne cm/rad	4.046×10^6

Table 7-6. Angular Resolution Table

N (bits)	Counts Per Revolution	Angular Resolution	
		Deg. Min., Sec.	Rad., Millirad.
1	2	180.0 deg.	3.14 rad.
2	4	90.0	1.57
3	8	45.0	.785
4	16	22.5	.393
5	32	11.3	.196
6	64	5.63	.0982
7	128	2.81	.0491
8	256	1.41	.0245
9	512	42.2 min.	12.3 millirad
10	1024	21.1	6.14
11	2048	10.5	3.07
12	4096	5.27	1.53
13	8192	2.64	.767
14	16384	1.32	.383
15	32768	39.6 sec.	.192
16	65536	19.8	.0959
17	131072	9.89	.0479
18	262144	4.95	.0240
19	524288	2.47	.0120
20	1048576	1.24	.00599
21	2097152	.618	.00300
22	4194304	.309	.00150
23	8388608	.154	.000749
24	16777216	.077	.000375

Table 7-7. Angles to Decimals

Minutes Into Decimals of a Degree				Seconds Into Decimals of a Degree			
Min.	Dec. of Degree	Min.	Dec. of Degree	Sec.	Dec. of Degree	Sec.	Dec. of Degree
1	0.016667	31	0.516667	1	0.000278	31	0.008611
2	0.033333	32	0.533333	2	0.000556	32	0.008889
3	0.050000	33	0.550000	3	0.000833	33	0.009167
4	0.066667	34	0.566667	4	0.001111	34	0.009444
5	0.083333	35	0.583333	5	0.001389	35	0.009722
6	0.100000	36	0.600000	6	0.001667	36	0.010000
7	0.116667	37	0.616667	7	0.001944	37	0.010278
8	0.133333	38	0.633333	8	0.002222	38	0.010556
9	0.150000	39	0.650000	9	0.002500	39	0.010833
10	0.166667	40	0.666667	10	0.002778	40	0.011111
11	0.183333	41	0.683333	11	0.003056	41	0.011389

Table 7-7. Angles to Decimals (Cont.)

Minutes Into Decimals of a Degree				Seconds Into Decimals of a Degree			
Min.	Dec. of Degree	Min.	Dec. of Degree	Sec.	Dec. of Degree	Sec.	Dec. of Degree
12	0.200000	42	0.700000	12	0.003333	42	0.011667
13	0.216667	43	0.716667	13	0.003611	43	0.011944
14	0.233333	44	0.733333	14	0.003889	44	0.012222
15	0.250000	45	0.750000	15	0.004167	45	0.012500
16	0.266667	46	0.766667	16	0.004444	46	0.012778
17	0.283333	47	0.783333	17	0.004722	47	0.013056
18	0.300000	48	0.800000	18	0.005000	48	0.013333
19	0.316667	49	0.816667	19	0.005278	49	0.013611
20	0.333333	50	0.833333	20	0.005556	50	0.013889
21	0.350000	51	0.850000	21	0.005833	51	0.014167
22	0.366667	52	0.866667	22	0.006111	52	0.014444
23	0.383333	53	0.883333	23	0.006389	53	0.014722
24	0.400000	54	0.900000	24	0.006667	54	0.015000
25	0.416667	55	0.916667	25	0.006944	55	0.015278
26	0.433333	56	0.933333	26	0.007222	56	0.015556
27	0.450000	57	0.950000	27	0.007500	57	0.015833
28	0.466667	58	0.966667	28	0.007778	58	0.016111
29	0.483333	59	0.983333	29	0.008056	59	0.016389
30	0.500000	60	1.000000	30	0.008333	60	0.016667

Table 7-8. Inch-Millimeter Equivalents of Decimal and Common Fractions from 1/64 to 1 in.

Inch	1/2's	1/4's	8ths	16ths	32nds	64ths	Millimeters	Decimals of an Inch
					1	1	0.397	0.051 625
						2	0.794	0.031 25
						3	1.191	0.046 875
				1	2	4	1.588	0.062 5
						5	1.984	0.078 125
					3	6	2.381	0.093 75
						7	2.778	0.109 375
			1	2	4	8	3.175	0.125 0
						9	3.572	0.140 625
					5	10	3.969	0.156 25
						11	4.366	0.171 875
				3	6	12	4.762	0.187 5

Table 7-8. Inch-Millimeter Equivalents of Decimal and Common Fractions from 1/64 to 1 in. (Cont.)

Inch	1/2's	1/4's	8ths	16ths	32nds	64ths	Millimeters	Decimals of an Inch		
1	1	2	4	8	16	13	5.159	0.203	125	
						14	5.556	0.218	75	
					15	5.953	0.234	375		
				4	8	16	6.350	0.250	0	
						17	6.747	0.265	625	
					18	7.144	0.281	25		
			5	10	20	19	7.541	0.296	875	
						20	7.938	0.312	5	
					11	21	8.334	0.328	125	
				22		8.731	0.343	75		
				23		9.128	0.359	375		
				3	6	12	24	24	9.525	0.375
		25	9.922					0.390	625	
		13	26				26	10.319	0.406	25
						27	10.716	0.421	875	
			7			14	28	11.112	0.437	5
		29					11.509	0.453	125	
		15			30	30	30	11.906	0.468	75
			31				12.303	0.484	375	
			16			32	12.700	0.500	0	
					17	33	33	13.097	0.515	625
							34	13.494	0.531	25
			18			35	35	13.891	0.546	875
		36		14.288	0.562		5			
	19	37		37	37	14.684	0.578	125		
			38		15.081	0.593	75			
			20	39	39	15.478	0.609	375		
		40			15.875	0.625	0			
		11		21	41	41	16.272	0.640	625	
			42			16.669	0.656	25		
	22		43		43	17.066	0.671	875		
				44	17.462	0.687	5			
			23	45	45	17.859	0.703	125		
	46				18.256	0.718	75			
	24	47		18.653	0.734	375				
		48		19.050	0.750	0				

Table 7-8. Inch-Millimeter Equivalents of Decimal and Common Fractions from 1/64 to 1 in. (Cont.)

Inch	1/2's	1/4's	8ths	16ths	32nds	64ths	Millimeters	Decimals of an Inch
						49	19.447	0.765 625
					25	50	19.844	0.781 25
						51	20.241	0.796 875
				13	26	52	20.638	0.812 5
						53	21.034	0.828 125
					27	54	21.431	0.843 75
						55	21.828	0.859 375
			7	14	28	56	22.225	0.875 0
						57	22.622	0.890 625
					29	58	23.019	0.906 25
						59		0.921 875
				15	30	60	23.812	0.937 5
						61	24.209	0.953 125
					31	62	24.606	0.968 75
						63	25.003	0.9M 375
1	2	4	8	16	32	64	25.400	1.000 0

8. GLOSSARY

ACCURACY — The ratio of the error to the full-scale output or the ratio of the error to the output, as specified, expressed in percent. Accuracy may be expressed in terms of units of input, or as within $\pm x$ percent of full-scale output. Use of the term accuracy should be limited to generalized descriptions of characteristics. It should not be used in specifications. The term error is preferred in specifications and other specific descriptions of transducer performance.

AMBIENT CONDITIONS — The conditions (pressure, temperature, etc.) of the medium surrounding the case of the transducer.

AMBIGUITY — Inherent error arising from multiple bit changes in a polystrophic code when going from one digit to an adjacent digit; can usually be corrected through proper logic design.

AND GATE — A logic element or circuit operating such that if all inputs are true (binary 1), the output indicates true; and that if one or more inputs are false (binary 0), the output is false.

ANGULAR MISALIGNMENT — The maximum deviation in perpendicularity between the encoder shaft and the face of the mounting surface, represents the total of shaft misalignment, shaft runout, and mounting face runout measured at the worst respective positions.

A NTIAMBIGUITY LOGIC — Prevents ambiguous outputs from encoders using polystrophic codes.

AXIAL LOAD, MAXIMUM — The maximum axial force that may be applied in either direction without affecting encoder performance (life).

BINARY — The term referring to the number 2 or to the number system with a radix of 2.

BINARY CODED DECIMAL — A decimal notation in which the individual decimal digits are each represented by a group of binary bits. Usually associated with codes of four or more bits used to define the Arabic numbers 0 through 9.

BINARY NUMBER — A counting system in which only two digits are used (1,0).

BIT — An abbreviation for BInary digiT and has the value of either true (1) or false (0), on or off, the basic unit of the binary system.

CAPACITY — The total number of counts available from an encoder.

CIRCULAR MIL — $1 \text{ cmil} = (B/4) 10^{-6} \text{ in}^2$.

CODE — A number of binary digits uniquely arranged to define each position in a given number system.

COMMAND — An instruction coded in binary form.

COMPENSATION — Provision of a supplemental device, circuit, or special materials to counteract known sources of error.

COUNT ERROR — An omission or mistake in coded output.

COUNT TRANSITION POINT — The midpoint of boundary between two adjacent output counts.

COUNTS PER TURN — The total number of code positions per 360° of encoder shaft rotation.

CYCLE PER SECOND — IEC recommends the new name hertz (Hz) for this unit, and hertz has been adopted by the Conference Generale des Poids et Mesures.

DEGREE CELSIUS — The word centigrade (for the Celsius temperature scale) was abandoned by the Conference Generale des Poids et Mesures in 1948.

DIGIT — A character used to represent integers smaller than the radix, e.g., 0 through 9 in decimal notation.

ERROR — The algebraic difference between the indicated value and the true value of the input.

EXCITATION — The external electrical voltage and/or current applied to a transducer for its proper operation.

EXCLUSIVE OR GATE — A logic element with two inputs and one output having the property that if either input is true, but not both true, the output is true and if both inputs are true or both inputs false the output is false.

FLIP-FLOP — A circuit containing logic elements capable of assuming either one of two stable states at any given time.

FREQUENCY RESPONSE — The change in amplitude of the output waveform, with respect to frequency of the input.

GATE — A logic element having one output channel and one or more input channels, i.e., AND gate, OR gate, etc.

HERTZ — New name for cycles per second.

INCLUSIVE OR GATE — A logic element or circuit which operates such that the output is false only when all inputs are false.

INTERFACE — Interconnections of one system element to another.

LOAD IMPEDANCE — The impedance presented to the output terminals of a transducer by the associated external circuitry.

MIL = 0.001 inch.

MONOSTROPHIC CODE — A binary code in which only one bit changes between any two adjacent code positions.

MOUNTING ERROR — The error resulting from mechanical deformation of the transducer caused by mounting the transducer and making all input and electrical connections.

NULL — A condition, such as of balance, which results in a minimum absolute value of output.

OCTAL — Pertaining to a number system with a radix of eight.

OPERATING SPEED, MAXIMUM — The maximum angular velocity at which an encoder may operate and still maintain specified accuracy.

OR GATE — A logic component having the property that if any one input is true the output is true and the output is false only when all inputs are false.

OUTPUT — The electrical quantity, produced by a transducer, which is a function of the applied input.

OUTPUT IMPEDANCE — The impedance across the output terminals of a transducer presented by the transducer to the associated external circuitry.

PARITY BIT — A binary digit appended to an array of bits to make the sum of all bits always odd or always even (synonymous with odd-even check).

POLYSTROPHIC CODE — A binary code in which, for at least one count transition, two or more bits are required to change simultaneously in going from one adjacent code position to another.

QUANTIZATION ERROR — The inherent fixed error associated with digitizing an analog shaft position in that a continuous form of data is being replaced by noncontinuous increments.

RADIX — The number of digit symbols in a number system; the numerical base of the number system.

RELIABILITY — The probability that an observed or sample value of encoder output is exactly equal to the required output.

REPEATABILITY — The ability of a transducer to reproduce output readings when the same input value is applied consecutively, under the same conditions, and in the same direction.

RESET— To restore a storage device to a prescribed state.

RESOLUTION— A measure of the smallest change of input which can be detected by the encoder.

RETICLE— The pattern of lines and spaces that is stationary with respect to the optical encoders light sensor.

SLEW SPEED— The maximum velocity to which an encoder may be accelerated and still regain full accuracy when slowed below the maximum speed.

STABILITY.— The ability of a transducer to retain its performance characteristics for a relatively long period of time.

STORAGE— Pertaining to a device into which data can be entered, in which it can be held, and from which it can be retrieved at a later time.

TRANSDUCER— A device which provides a usable output in response to a specified input.

ZERO REFERENCE— An output signal produced once in some specified displacement (usually once per revolution). Used for powerfail recovery, error checking, or for calibration.