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Superior Electric

DESIGN ENGINEER'S GUIDE TO AC SYNCHRONOUS MOTORS



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1.0 CONSTRUCTION AND PRINCIPLES OF OPERATION

The SLO-SYN motor is unique in that it has the capability of being operated as an AC synchronous, constant speed motor or as a phase switched DC stepper motor. In either case, it is classified as a permanent magnet inductor motor.

Figure 1 shows the simplicity of the basic motor construction. Note that the motor has no brushes, commutators, belts or slip rings. Essentially, the motor consists of a rotor and a stator which make no physical contact at any time, due to a carefully maintained air gap. As a result of the simple construction, the motor provides long life and high reliability. A continuous running life of five years can be expected.

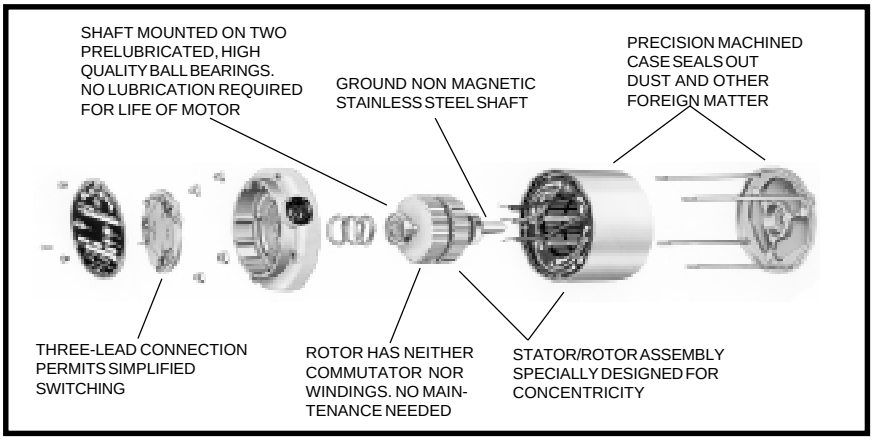


FIGURE 1

In a typical 72 rpm motor, the stator has eight salient poles with a two-phase, four-pole winding (see Figure 2). Poles designated N1, S3, N5 and S7 are energized by one phase, while Poles N2, S4, N6 and S8 are controlled by the opposite phase.

The stator teeth are set at a pitch of 48 teeth for a full circle, although there are actually only 40 teeth, as one tooth per pole has been eliminated to allow space for the windings. The windings of each four alternate poles are connected in series.

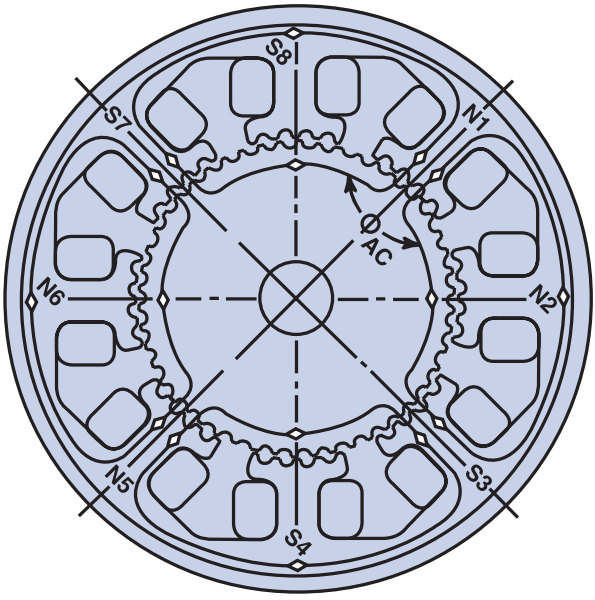


FIGURE 2

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The rotor shown in Figure 3 consists of a nonmagnetic drive shaft, and an axially magnetized permanent magnet. The splines, or teeth, of the pole pieces are offset by one-half a tooth pitch to permit the use of a common stator magnetic structure and windings.One pole piece is a south pole and the other, a north pole.



FIGURE 3

Unlike the stator teeth, rotor teeth of a typical motor are at a pitch of 50 teeth for a full circle, two more than in the stator. Because of this difference, only two rotor teeth and two stator teeth can be perfectly aligned simultaneously. The magnetic arrangement of the rotor creates a south pole over the entire periphery of one-half of the rotor and a north pole over the other half. An amount of residual, or unenergized, torque is provided in the rotor, which results in the motor having the ability to stop instantaneously.

2.0 INTRODUCTION

A SLO-SYN motor operating from AC power is an extremely effective method of obtaining precise motion control. Operation simply involves connecting the SLO-SYN motor to the AC power line, incorporating a phase shifting network consisting of a resistor/capacitor or just a capacitor, and using a three-position switch “forward”, “off” and “reverse” control. The phase shifting network provides the capacitive reactance necessary to produce a 90° phase shift between the two windings.

2.1 PRINCIPAL ADVANTAGES OF THIS TYPE OF MOTOR ARE AS FOLLOWS:

1. **Simple circuitry**
2. **Bidirectional control**
3. **Instantaneous start, stop and reverse**
4. **Starting and running current are identical**
5. **Stalling causes no damage**
6. **Torque can be increased by increasing voltage**
7. **Residual (Power Off) torque is always present**
8. **Holding torque can be increased by applying DC voltage**
9. **Long life and exceptional reliability**

We will now discuss these features along with other aspects of the the SLO-SYN AC Synchronous Motor in more detail.

2.2 AC IDENTIFICATION SYSTEM

The type number identification system for SLO-SYN Synchronous Motors is straightforward and easily understood. For example, in type number SS25, the “SS” indicates “Standard SLO-SYN”, which has a synchronous shaft speed of 72 rpm at 120 volts, 60 hertz. The “25” in the type number designates the torque rating of the motor in ounce-inches. Figure 4 shows the letter designations which are offered and Figure 5 shows how the two elements of the type number identify the characteristics of the motor.

Understanding the motor identification system makes it easy to select the correct type number. For example, if an application requires a synchronous motor with a

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speed of 72 rpm and a torque output of 200 ounce-inches at 120 volts, 60 hertz, the SS221 motor, which produces 220 ounce-inches of torque at 72 rpm, could be specified. Consult the SLO-SYN motor catalog for a complete description of the motor identification system and a list of the motors available.

AC IDENTIFICATION SYSTEM

Type	Speed (rpm @ 60 Hertz)
KS/SS	72
TS	200

FIGURE 4

IDENTIFICATION SYSTEM EXAMPLE

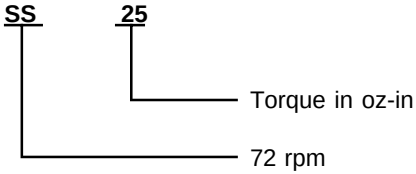


FIGURE 5

2.3 SINGLE-PHASE OPERATION

Figure 6 contains a diagram showing the connections for operating a SLO-SYN motor as a three-lead, reversible motor from a single-phase source. Since a SLO-SYN motor is inherently a two-phase or a three-phase device, depending on model, a phase shifting network is required to convert the single-phase excitation into the two- or three-phase excitation required. Two-phase motors require a resistor and a capacitor for the phase-shifting network, while three-phase motors need only a capacitor. The connections in Figure 6 are for a two-phase motor.

Specific phase shifting component values are required for each motor and these values are from published Ratings and Specifications charts in our catalog. Unless otherwise specified, the component values listed in the catalog will provide satisfactory operation at any frequency between 50 and 60 hertz. Different values may be necessary at other frequencies to give the required 90° phase shift. It may also be necessary to adjust the applied voltage level.

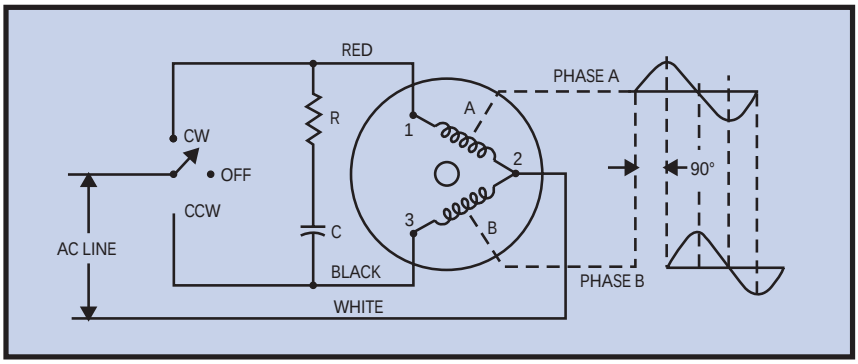


FIGURE 6

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"Tuning" the phase-shifting by adjusting the component values can help achieve maximum torque, minimum vibration, or any combination thereof. The correct phase-shifting component values are necessary for proper operation of the motor. Without the proper values, motor direction will be completely random. There will also be a tendency to reverse in response to even slight load changes and, at times, the motor may fail to start. Incorrect phase-shifting component values will also cause erratic, unstable operation.

The Phase-shifting network components are normally mounted externally. Certain motor models are available with the components mounted in a housing on the rear of the motor. Consult the catalog for availability of these models.

2.4 STARTING AND STOPPING CHARACTERISTICS

Virtually instant starting and stopping characteristics are among the principal advantages of a SLO-SYN motor. Generally, the motor will start within 1-1/2 cycles of the applied frequency and will stop within 5 mechanical degrees. Figure 7 shows a typical starting curve for a 72 rpm SLO-SYN motor. The motor will start and reach its full synchronous speed within 5 to 25 milliseconds. The unusually short stopping distance of a SLO-SYN motor is obtained by simply deenergizing the motor. No mechanical or electrical braking is necessary. The quick stopping is the result of the slow rotor speed and the presence of a no-load reluctance torque produced by the permanent magnet and the tooth construction of the stator and rotor.

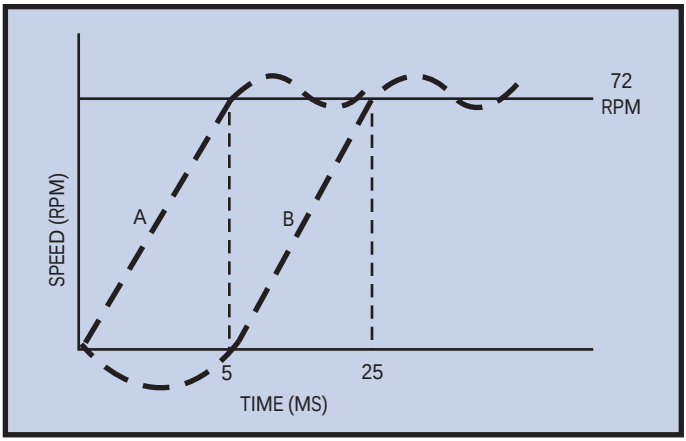


FIGURE 7

2.5 STARTING IN THE DESIRED DIRECTION

The two conditions which determine the instantaneous starting direction of a SLO-SYN motor are the position of the rotor prior to start and what portion of the AC sine wave is apparent when it is first applied to the motor windings. Curve A in Figure 7 shows the motor starting in the correct direction. The motor may also momentarily start in the wrong direction, then quickly reverse and rotate in the correct direction (Curve B in Figure 7). In most instances, this action is negligible and is of no consequence. The motor will still start within the 25 milliseconds stated earlier. In applications where no motion in the opposite direction can be tolerated, external control circuits employing "Zero Crossover" techniques must be used.

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2.6 STARTING AND RUNNING CURRENT

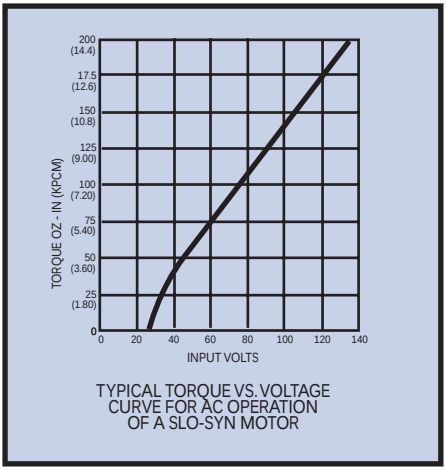
Because of the nature of the permanent magnet inductor motor, there is no high inrush current when power is applied. The windings are excited by the alternating current, with no current being conducted through the rotor or through brushes. Because energization of the SLO-SYN motor merely involves energizing the windings, the starting, running and stall currents are, for all practical purposes, identical. Therefore the engineer designing a system need not be concerned about high inrush currents with the SLO-SYN motor. Consult the motor catalog for current requirements of the various SLO-SYN motor models

2.7 STALLING CAUSES NO DAMAGE

Because of the characteristics described in Section 2.6, a SLO-SYN motor does not draw excessive current when the motor is stalled. Since the windings are merely being energized by the alternating current, it doesn't matter whether the rotor is in motion or at a standstill. Also, no detrimental overheating will take place. Therefore, if this motor were used in an application in which it was operating a remotely controlled valve, and the motor stalled, there would be no possibility of system damage due to overheating of the motor, etc. One precaution must be noted: in this stalled condition, the motor will oscillate severely, eventually causing bearing failure.

2.8 TORQUE VERSUS VOLTAGE

As shown in Figure 8, the torque output of a SLO-SYN motor is linearly proportional to the applied voltage.Primarily for intermittent operation, this capability can be used to increase the torque output by increasing the voltage. For example, assume the steady-state torque requirement for a given application is 110 ounce-inches. Normally a standard 130 ounce-inch motor would be adequate for the application. If, however, the application is subject to wide variations in line voltage, the 20 ounce-inch safety margin may be inadequate. A simple solution is to increase line voltage by approximately 10 volts with a step-up transformer or a POWERSTAT® Variable Transformer. Because operation at higher than rated voltage will cause an increase in motor temperature rise, the motor shell temperature must be monitored and must not be permitted to go above 100° C. Obviously, where more torque is needed, the next larger motor size should be used. The torque/voltage relationship should only be used to increase torque when a larger motor will not fit into the space available.



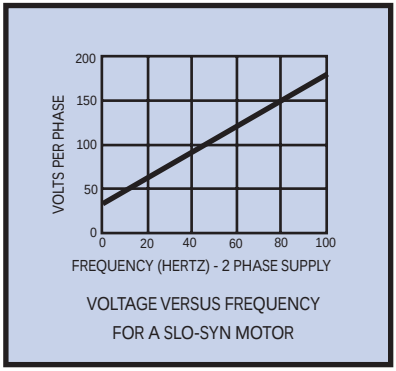
TYPICAL TORQUE VS. VOLTAGE CURVE FOR AC OPERATION OF A SLO-SYN MOTOR

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2.9 SPEED VERSUS FREQUENCY

The speed of a SLO-SYN motor is directly proportional to the applied frequency. Because the winding impedance is also a function of frequency, a constant-torque output will only be obtained at different excitation frequencies by varying line voltage, as shown in Figure 9. Only when the motor is operating from a two-phase or three-phase supply (depending on motor model) can different synchronous speeds be easily achieved by varying the line frequency.

When varying the frequency of a single-phase system, the phase shifting component values must be changed to provide the necessary 90° phase shift at each new operating frequency. Figure 10 shows the speeds at different frequencies for the two standard SLO-SYN motor series.



VOLTAGE VERSUS FREQUENCY
FOR A SLO-SYN MOTOR

FIGURE 9

FREQUENCY (HERTZ)	KS/SS SERIES	TS SERIES
10	12	33.4
20	24	66.8
30	36	100.2
40	48	133.6
50	60	167.0
60	72	200.0
70	84	233.8
80	96	267.2
90	108	300.6
100	120	334.0

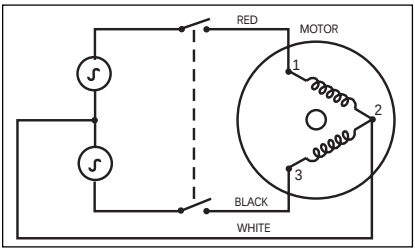
FIGURE 10

3.0 TWO-PHASE OR THREE-PHASE OPERATION

In some applications, SLO-SYN AC Synchronous Motors are operated directly from a two-phase or a three-phase source. Connections for two-phase motor operated from a two-phase supply are shown, no phase-shifting network is needed as long as the supply provides the necessary phase shift between the windings (90° for two-phase motors; 120° for three-phase motors). From 0 hertz to approximately 100 hertz, motor speed can be varied by simply changing the supply frequency. The chart in Figure 10 shows the speeds obtainable at different frequencies for the SS and TS series of motors. Depending on the motor used and the torque and inertia requirements, a motor may fail to start at frequencies above 100 hertz. Note that, as

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shown in Figure 9, voltage must be adjusted as frequency is changed.



Typical Wiring for Operation From a Two-Phase Source

FIGURE 11

3.1 STARTING HIGH INERTIAL LOADS

Because of the rapid starting characteristics of a SLO-SYN motor, a maximum moment of inertia value is listed for each motor model. These values represent the maximum inertial load which specific motor models can start when driving the load through a rigid coupling. Inertial loads five to ten times these values can be started by using a flexible coupling between the motor shaft and the load. The flexible coupling should allow approximately 5° of flex before the full inertial load is "seen" by the motor shaft. The coupling can be as simple as a rubber coupling between the motor and the load, or it could be a chain with sufficient slack. Timing belts are also used as load coupling devices and, in many cases, will provide sufficient flex as well as serve as a smooth and quiet power transmission device. Figure 12 shows two typical flexible couplings.

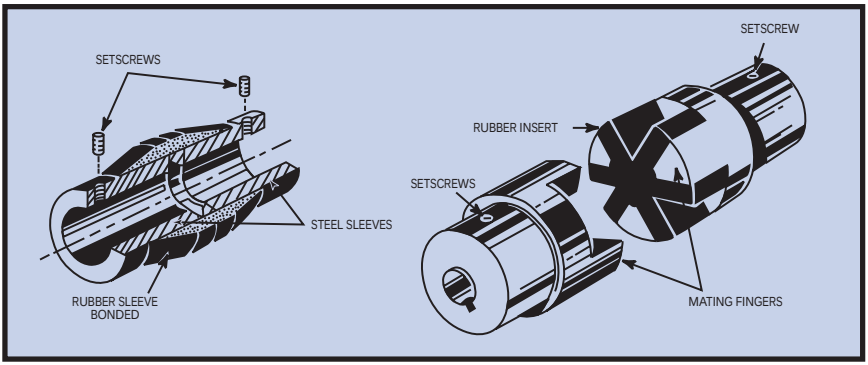


FIGURE 12

3.2 PARALLEL MOTOR OPERATION

Any number of SLO-SYN motors may be operated in parallel if their total current requirement does not exceed that of the power supply. It is important to realize, however, that due to the starting characteristics of this type of motor, mechanical synchronization of parallel operated motors is not practical. As mentioned earlier, the two conditions that determine the direction of rotation are the position of the rotor prior to start and the portion of the sine waveform apparent when the voltage is applied. Because of these variables, one motor may start within a 5 millisecond period, while another motor operated in parallel with the first may take up to 25 milliseconds to start. This will occur because the rotor of the second motor was in a slightly different position at the start of the cycle. This situation was previously illustrated in Figure 7.

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3.3 HOLDING TORQUE

Some applications require more holding torque than the small residual torque provided by the permanent magnet rotor. To increase the holding torque, DC voltage can be applied to one or both motor windings when the motor is in the off condition. Connections which can be used to accomplish this are shown in Figure 13.

With DC voltage applied to one winding, the holding torque will be increased approximately 20% over the rated torque of the motor. When DC voltage is applied to both motor windings, holding torque will be approximately 1-1/2 times the rated torque.

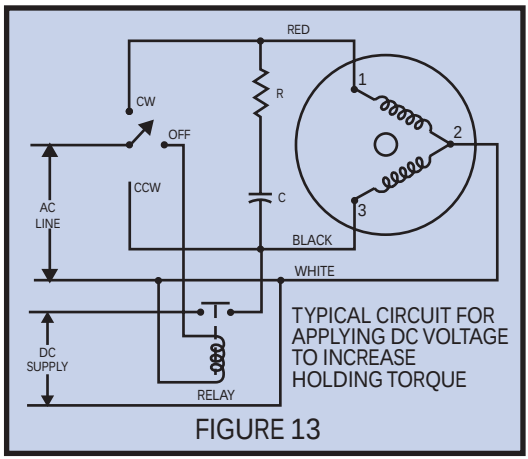


FIGURE 13

When DC voltage is applied to the windings, the motor may jump into a position of maximum magnetic attraction. The degree of movement depends on the position of the rotor relative to the stator when the DC voltage is applied and can be up to ±3.6° for an SS series motor. Figure 14 shows the holding torque available for various motor models when DC voltage is applied.

FIGURE 14

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3.4 EFFECT OF GEARING

The use of gearing with a SLO-SYN motor allows a reduction in speed and an increase in output torque when gearing down. Under “gearing down” conditions, torque is increased and output speed decreased by the factor of the gear ratio. For example, an SS91 motor produces 90 ounce-inches of torque at 72 rpm. If 4:1 step-down gearing is used between the motor and the load, the motor output torque would be approximately 360 ounce-inches at a speed of 18 rpm.

The mechanical advantage of gearing is most apparent in dealing with inertia as the inertia moving capability is affected by the square of the gear ratio. Again, assume 4:1 step-down gearing is being used with an SS91 motor. The SS91 has a maximum moment of inertia capability of 1.6 lb-in^2. With 4:1 gearing, however, the maximum moment of inertia is increased 16 times and would become approximately 25.6 lb-in^2 (42 = 16 x 1.6 lb-in^2).

Timing belts and pulleys are also widely used and provide a “softer” coupling with the same overall effect as steel gearing. Some SLO-SYN motors are available with “in-line” planetary type gearheads. A complete listing of these “SLO-SYN AC Gearmotors” can be found in the motor catalog.



3.5 THE SELECTION PROCESS

Selecting the correct AC synchronous motor for a particular application is a relatively simple task. The most important parameters are:

1. **Speed (rpm)**
2. **Torque (ounce-inches)**
3. **Inertia (lb-in^2)**

Since the standard available speeds of SLO-SYN motors are 72 and 200 rpm, the two key variables become torque and inertia. Of the two, inertia has always been the least understood parameter and one that often serves as a “trap” if overlooked. For example, assume an application requires 35 ounce-inches torque and the inertia is 2 lb-in^2. A typical initial reaction is to select an SS91 motor, rated at 90 ounce-inches, simply because the application requires only 35 ounce-inches torque. However, the SS91 motor is only capable of moving 1.6 lb-in^2. Therefore, the SS91 motor would be unable to start the load. For this application as described, the best choice would be the SS221 motor, which provides 220 ounce-inches of torque and is rated for a maximum moment of inertia of 2.5 lb-in^2.

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As can be seen from this example, it is important to know the *maximum moment of inertia* which will be reflected to the motor. Only when all the parameters are known can an intelligent decision be made in selecting the correct motor for the application. Formulas for calculating torque and inertia are follow.

a. TORQUE (oz-in) = Fr

where F = Force (in ounces) required to drive the load
r = Radius (in inches)

Force can be measured using a pull type spring scale. The scale may be attached to a string that is wrapped around a pulley or handwheel attached to the load. If the scale reading is in pounds, it must be converted into ounces to obtain a torque value in ounce-inches.

For example, a 4" diameter pulley requires a 2 pound pull on the scale to rotate it.

$$\mathbf{F} = 2 \text{ pounds} \times 16 = 32 \text{ ounces}$$

$$\mathbf{r} = \frac{4"}{2} = 2"$$

$$\mathbf{TORQUE} = 32 \times 2 = 64 \text{ ounce-inches}$$

b. MOMENT OF INERTIA

$$(\text{lb-in}^2) = \frac{Wr^2}{2} \text{ for a disc}$$

or $$(\text{lb-in}^2) = \frac{W}{2}(r_1^2 + r_2^2) \text{ for a cylinder}$$

where W = Weight (in pounds)
r = Radius (in inches)

For example, a load is a 8" diameter gear weighing 8 ounces

$$W = \frac{8}{16} = 0.5 \text{ pound}$$

$$r = \frac{8"}{2} = 4"$$

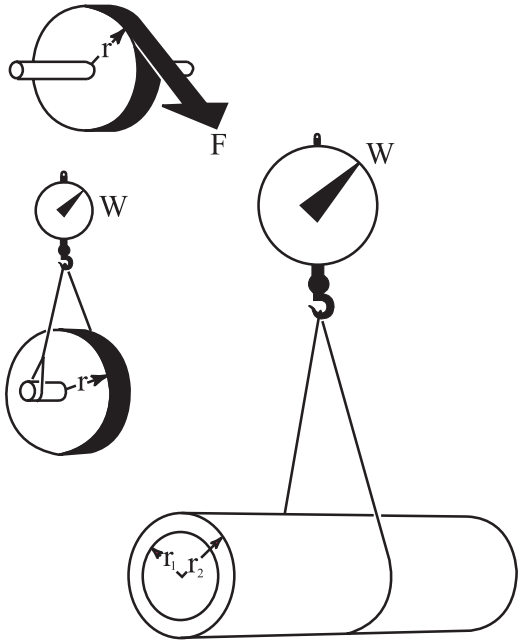
$$\textbf{MOMENT OF INERTIA} = \frac{0.5 \times (4)^2}{2} = 4 (\text{lb-in}^2)$$

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GEARS AND PULLEYS

When the load is to be driven through gears or pulleys, the torque should be decreased or increased by the overall ratio. For example, if the load is 90 ounce-inches and it is to be driven through a step-down ratio of 3:1, the required torque is 30 ounce-inches.

Load inertia should be decreased or increased by the square of the ratio. For example, with a load inertia of 4 pound-inches^2 and a 2:1 step-down ratio, the effective inertia would be 1 pound-inch^2 plus the inertia of the first gear or pulley.



INERTIA CONVERSION FACTORS

slug-ft^2 x 4600	=	lb-in^2
lb-ft^2 x 144	=	lb-in^2
oz-in^2 x 0.0625	=	lb-in^2
lb-ft-sec^2 x 4600	=	lb-in^2
lb-in-sec^2 x 384	=	lb-in^2
oz-in-sec^2 x 24	=	lb-in^2
gm-cm^2 x 0.000342	=	lb-in^2
kp-m-sec^2 x 33,500	=	lb-in^2

METRIC-DECIMAL EQUIVALENTS

1 inch	=	2.54 cm
1 cm	=	0.3937 inch
1 pond (gm)	=	0.03527 oz
1 oz	=	28.35 pond (gm)
1 kp (kg)	=	2.205 pound
1 gm-cm	=	0.0139 oz-in
1 kg-cm	=	1 kp-cm = 13.9 oz-in
1 hp	=	746 watts

3.6 CAPABILITIES

SLO-SYN AC Synchronous Motors produce torque outputs ranging from 25 ounce-inches to 1800 ounce-inches in various frame sizes. In addition to the wide variety of torque ratings and frame sizes, special capability motors such as double-ended shaft, militarized, limited vacuum, high temperature, radiation resistant, dust-ignition proof and explosion-proof types are available.

Gearmotors and motors with phase-shifting components are also offered on some models.

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3.7 AC APPLICATIONS

SLO-SYN AC Synchronous Motors provide low, constant-speed positioning control with minimum control circuitry and maximum life. The following is a partial list of possible applications.

a. Valve controls
b. Timing belt drives
c. Conveyor systems
d. Card positioning
e. X-Ray scanning
f. Antenna rotators
g. Film handling
h. Microfilm scanners
i. Paper feed
j. Furnace damper controls
k. Tape dispensers
l. Remote control of switches, rheostats, etc.
m. X-Y positioning
n. Textile edge guide controls
o. Printing press ink pump control
p. Generators
q. Automated welding equipment
r. Paper handling
s. Medical pumps
t. Fluid metering

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DESIGN ENGINEER'S GUIDE TO DC STEPPER MOTORS

1.0 PURPOSE

The purpose of this guide is to acquaint the designer with basic characteristics of DC stepper motors and associated drives. Their advantages and capabilities as digital motion control devices are also discussed.

1.1 BASIC DESCRIPTION

The stepper motor is a device which translates electrical pulses into mechanical movements. The output shaft rotates or moves through a specific angular rotation for each incoming pulse or excitation. This angle or displacement per movement is repeated precisely with each succeeding pulse translated by appropriate drive circuitry. The result of this precise, fixed and repeatable movement is the ability to accurately position. Unlike a conventional motor, which has a free running shaft, the stepper motor shaft rotates in fixed, repeatable, known increments. The stepper motor therefore allows control of load velocity, distance and direction. Initial positioning accuracy of a load being driven by a stepper motor is excellent. The repeatability (the ability to position through the same pattern of movements a multiple number of times) is even better. The only system error introduced by the stepper motor is its single step error, which is generally less that 5% of one step. Most significantly, this error is noncumulative, regardless of distance positioned or number of times repositioning takes place. The stepper motor is generally controlled by a DC power supply and drive/logic circuitry which will be discussed in this guide.

1.2 STEPPER MOTOR TECHNOLOGY

As the use of stepper motor systems has increased in a broad base of applications, terminology has evolved which required definition.

A. Step Angle - This is the specific angular increment the motor shaft will move each time the winding polarity is changed. It is specified in degrees.

B. Steps Per Revolution - This term describes the total number of steps required for the motor shaft to rotate 360°, or one complete revolution. The number is calculated by dividing the step angle into 360°.

C. Steps Per Second - This is the number of steps accomplished by the motor in one second of time. This figure replaces the rpm value of a standard drive motor. See Section 7 for formulas used to calculate this value.

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D. Step Accuracy - Defined as positional accuracy tolerance. This value is generally expressed in percent and indicates the total error introduced by the stepper motors in a single step movement. The error is noncumulative, i.e., it does not increase as additional steps are taken. In a linear system with a resolution of 0.001 inch, a 3% accuracy motor would introduce a maximum of 0.00003 inch error into the system. This total error would not accumulate or increase with total distance moved or number of movements made.

E. Holding Torque - With the motor shaft at standstill (zero rpm condition), Holding Torque is the amount of torque, from an external source, required to break the shaft away from its holding position. It is measured with rated current and voltage applied to the motor. Holding torque is a basic characteristic of stepper motors and provides positioning integrity under standstill, or rest, conditions.

F. Residual Torque - This is the torque present at standstill under power off conditions and is a result of the permanent magnetic flux acting on the stator poles. Residual torque is present under power off conditions only with a motor of permanent magnet rotor design.

G. Step Response - When given a command to take a step, a stepper motor will respond within a specific time period. This time period, or "time for a single step", is a function of the torque-to-inertia ratio of the motor and of the characteristics of the electronic drive system. Ratings given are for no-load conditions and are generally expressed in milliseconds.

H. Torque-To-Inertial Ratio - This ratio is calculated by dividing the rated holding torque of the motor in ounce-inches by its rotor inertia in ounce-inch-seconds squared. The better the torque-to-inertia ratio, the better the step response. When dealing with step response problems, it is important to know the torque-to-inertia ratio of the motor.

I. Resonance - Stepper motors are a "spring response" system and, as such, have certain "natural" frequency characteristics. When a motor's natural frequency, or "resonance" is reached, an increase in the audible level of the motor's operation can be detected. In cases of server resonance, the motor may lose steps and/or oscillate about a point. The frequency at which this occurs depends on the motor and the load. In many applications, it may not occur to any perceptible degree. However, the designer should realize that this condition can exist and specific facts about the resonant characteristics of a particular motor should be obtained from the manufacturer.

J. Drives - This a broad term used to describe the circuitry which controls the stepper motor. It usually consists of a power supply, sequencing logic and power output switching components. These drives are generally categorized as Translators, Translator/Oscillators or Indexers.

K. Translator - An electronic control with circuitry to convert pulses into the switching sequence which will operate the motor one step for each pulse received. Translators usually have no counting capability.

L. Translator/Oscillator - Includes translator circuitry together with a built-in oscillator which can serve as a pulse source.

M. Indexer - An electronic control which includes the translator function plus additional circuitry to control the number of steps taken as well as direction and velocity.

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N. Pulse Rate - The rate at which windings are switched. Where one pulse equals one motor step, the pulse rate is also the motor stepping rate.

O. Ramping - This is the process of controlling the pulse frequency to accelerate the motor from base speed to running speed as well as to decelerate the motor from running speed to base speed. Ramping increases the ability to drive the motor and load to higher speeds, particularly with large inertial loads.

P. Slew Rate - An area of high speed where the motor can run unidirectionally in synchronism. However, it cannot start, stop or reverse at this rate. A stepper motor is brought to a slewing rate using acceleration and is then decelerated to stop under conditions where no step loss can be tolerated.

Q. Damping - Damping is defined as the reduction or elimination of step overshoot. It is used where settling down time is important,. Damping methods used include mechanical, electronic and viscous means.

1.3 STEP ANGLE

The step angle of a SLO-SYN Step Motor is 1.8°, equivalent to 200 steps per revolution.

2.0 BASIC CONSTRUCTION AND OPERATION

Operation of a stepper motor is related to basic permanent magnet theory, where "likes' repel and "opposites" attract. If the stator windings in Figure 1 are energized such that Stator A is the North Pole, Stator B is the South Pole and the permanent magnet rotor is positioned with its polarity as shown, it is impossible to determine the direction of rotation. However if, as shown in Figure 2, two additional Stator poles C and D are added and energized so that polarities appear as shown, we would then be able to dictate the direction of rotor rotation. In this case, the direction would be counterclockwise with the rotor aligning itself between the "average" South Pole and the "average" North Pole, as shown in Figure 3.

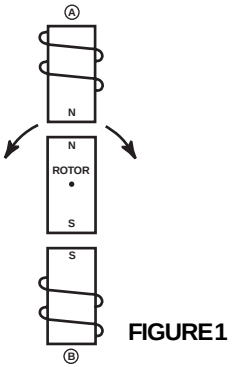


FIGURE 1

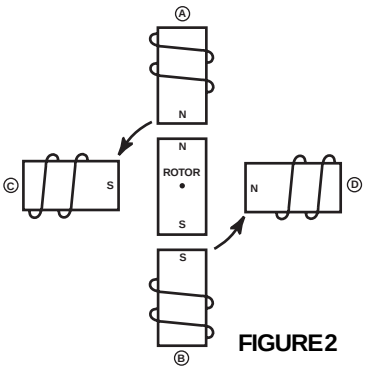


FIGURE 2

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To allow better single step resolution, four more stator poles are added and teeth are machined on each stator pole as well as on the rotor. In the final analysis, the number of teeth on the rotor determines the step angle that will be achieved each time the polarity of one winding is changed. The rotor/stator tooth configuration for a 1.8° stepper is shown in Figure 4.

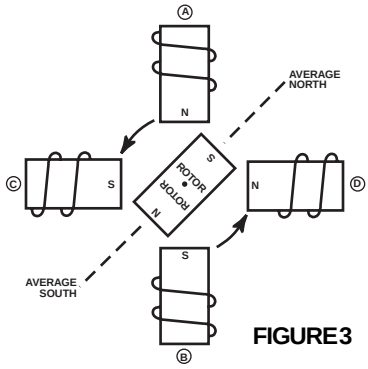


FIGURE 3

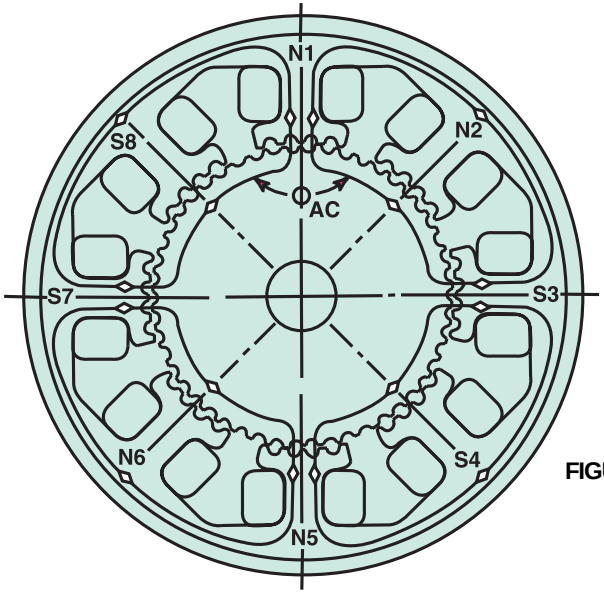


FIGURE 4

3.0 RATINGS

The chart lists typical ratings for SLO-SYN Stepper Motors as shown in our catalogs. While the voltage rating is straightforward, note that the current requirements are given in "amperes per winding." Using the typical four-step switching sequence, two windings are 'on' at any given time. Therefore, the total current requirement of the motor is twice the "amperes per winding" value given in the chart. Inductance and resistance values are also given "per winding."

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ELECTRICAL RATINGS

Motor Type			Typical Time For Single Stop (mS)	Nominal DC Volts	Rated Amperes for Winding	Nominal Resistance Per Winding (25°C) Ohms	Nominal Inductance Per Phase (Milli-Henrys)
2% Accuracy	3% Accuracy	5% Accuracy					
UNIPOLAR RATINGS (6-LEAD DRIVE)							
KM~060S03 KM~060S08	–	–	–	2.9 1.3	1.5 3.8	1.9 0.34	4.0 0.63
KM~061S02 KM~061S04 KM~061S08	–	–	–	6.4 3.0 1.7	1.0 2.1 3.8	6.4 1.5 0.46	18 3.5 1.1
KM~062S04 KM~062S06 KM~062S09	–	–	–	3.1 2.8 1.8	2.1 3.0 4.7	1.5 0.94 0.38	4.2 2.5 0.85
KM~063S04 KM~063S09	–	–	–	4.3 2.5	2.1 4.7	2.0 0.54	6.0 1.6
KM~091S02 KM~091S06 KM~091S08 KM~091S09	–	–	–	9.3 2.9 2.1 1.8	1.0 3.1 3.8 4.7	9.3 0.94 0.55 0.38	47 4.7 2.9 1.9
KM~092S09	–	–	–	2.5	4.6	0.54	2.8
KM~093S07 KM~093S10	–	–	–	4.4 3.5	3.5 4.8	1.3 0.72	8.3 4.5
–	M061~S02 M061~E02	–	2.5	5.0	1.0	5.0	9.57
–	M061~S08 M061~E08	–	2.0	1.25	3.8	0.33	0.635
–	M062~S04 M062~E04	–	2.8	4.2	1.9	2.2	5.89
–	M062~S06 M062~E06	–	–	2.6	3.1	0.88	2.0
–	M062~S09 M062~E09	–	2.2	1.65	4.7	0.35	0.8
–	M091-FC06	M091~S06	3.9	2.6	3.1	0.85	4.12
–	–	M091~E06	3.9	2.6	3.1	0.85	4.12
–	–	M091~E09	3.1	1.7	4.7	0.36	1.5
–	–	M092~E08	4.0	3.0	4.0	0.75	3.56
–	–	M092~E09	3.9	2.5	4.6	0.55	2.76
–	–	M093~E11	4.1	2.64	5.5	0.48	3.19
–	–	M093~E14	3.4	2.27	7.0	0.324	2.0
–	–	M111-FD12 M111-FD-8012	4.4	2.26	6.1	0.37	2.3
–	–	M112-FD12	5.5	3.66	6.1	0.80	5.3
–	–	M112-FJ-8012	5.5	3.66	6.1	0.60	5.3

~ = "L" for leads or "T" for terminal box

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ELECTRICAL RATINGS

Motor Type			Nominal DC Volts	Rated Amperes For Winding	Nominal Resistance Per Winding (25°C) Ohms	Nominal Inductance Per Phase (Milli-Henrys)
2% Accuracy	3% Accuracy	5% Accuracy				
4-CONNECTION STEP MOTORS						
KM~060F02 KM~060F05 KM~060F08 KM~060F11	–	–	3.8 1.7 1.1 1.0	1.1 2.7 4.0 5.3	3.6 0.64 0.28 0.19	16 2.5 1.0 0.63
KM~061F02 KM~061F03 KM~061F05 KM~061F08 KM~061F11	–	–	5.2 4.2 2.3 1.4 1.2	1.1 1.4 2.7 4.1 5.4	4.9 3.0 0.85 0.33 0.23	30 16 4.6 1.8 1.1
KM~062F03 KM~062F05 KM~062F07 KM~062F08 KM~062F13	–	–	4.4 3.1 2.5 2.0 1.3	1.5 2.5 3.3 4.1 6.6	2.9 1.3 0.75 0.49 0.20	17 7.1 3.4 2.5 0.85
KM~063F03 KM~063F04 KM~063F07 KM~063F08 KM~063F13	–	–	6.1 5.0 3.4 2.6 1.9	1.5 1.8 3.3 4.1 6.6	4.1 2.8 1.0 0.64 0.28	24 17 6.2 3.9 1.5
KM~091F05 KM~091F07 KM~091F13	–	–	3.0 2.5 1.3	2.7 3.3 6.6	1.1 0.76 0.19	11 7.5 1.9
KM~092F07 KM~092F13	–	–	3.5 1.7	3.3 6.5	1.1 0.27	11 2.9
KM~093F07 KM~093F08 KM~093F10 KM~093F14	–	–	4.9 4.0 3.2 2.5	3.4 4.0 5.1 6.8	1.4 0.99 0.63 0.36	18 13 8.3 4.5
– –	M061~F01 M061~F02	– –	8.0 6.3	0.5 1.0	15.9 6.3	61.0 25
	M062~F02 M062-~F03	–	6.6 4.2	1.0 1.5	6.8 2.8	33.0 13
–	M063~F03	–	5.4	1.5	3.6	18.0
–	–	M091~F02 M091~F06	6.8 3.0	1.0 3.0	6.8 1.0	52.0 10
–	–	M092~F04 M092-~F08	3.4 4.0	2.0 4.0	1.7 1.0	16.6 11
–	–	M093~F06 M093-~F08	4.5 3.9	3.0 4.0	1.5 0.96	16.9 13
–	–	M111-FF-401 M111-FF-206	4.0 3.5	3.4 5.0	1.14 0.70	17.7 9.2
–	–	MX111-FF-401U	4.0	3.4	1.14	17.7
–	–	M112-FF-401 M112-FF-206	1.95 3.0	4.0 6.0	0.49 0.49	8.80 8.80
–	–	MX112-FF-401	1.95	4.0	0.49	8.80
–	–	M113-FF-401	4.5	6.0	0.75	17

~ = "L" for leads or "T" for terminal box

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4.0 THE FOUR-STEP SWITCHING SEQUENCE

SLO-SYN Stepper Motors are normally operated using the four-step switching sequence. Each time one of the switches indicated in the chart is transferred, the motor takes a "step." After four steps, the same two windings will be "on" as when the sequence was started. The rotor moves one-fourth of a tooth pitch for every step taken; so for every four steps, the rotor moves one full tooth pitch. With 50 teeth on the rotor, four steps/full tooth pitch x 50 teeth/revolution = 200 steps per revolution. The step angle is, therefore, a function of the number of teeth on the rotor and the switching sequence.

FOUR STEP INPUT SEQUENCE (FULL-STEP MODE)*

STEP	SW1	SW2	SW3	SW4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF
1	ON	OFF	ON	OFF

See Figure 5 for switch wiring

5.0 THE EIGHT-STEP SWITCHING SEQUENCE (Half-Stepping)

The eight-step sequence is often called "electronic half-stepping." With this method, the rotor moves half its normal distance per step. For example, a 1.8° (200 step per revolution) motor would become a 0.9° (400 step per revolution) motor. The advantages of operating in this mode include finer resolution, the reduction of resonant amplitudes and greater speed capability.

EIGHT-STEP INPUT SEQUENCE (FULL-STEP MODE)*

STEP	SW1	SW2	SW3	SW4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF
1	ON	OFF	ON	OFF

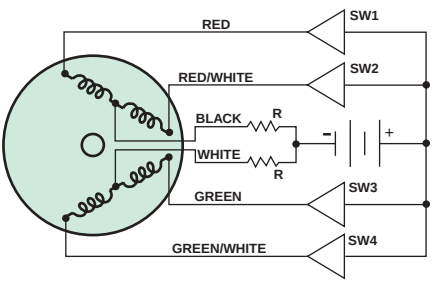


Figure 5

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6.0 TORQUE-SPEED RELATIONSHIP

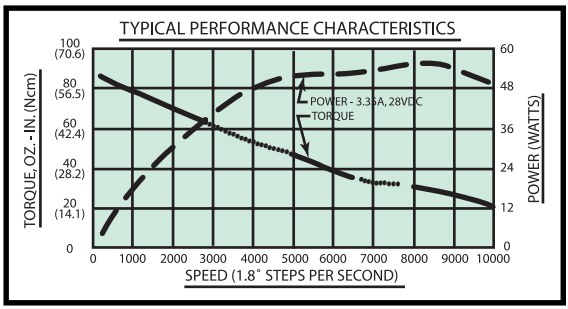
As the stepping rate increases, the back EMF (Electromotive Force) produced by the motor causes the current, and the motor torque, to decrease. Figure 6 shows a torque vs. speed curve for the M062-LE09 motor. Note that at standstill (zero steps per second) the torque output is 85 ounce-inches while at 2000 steps per second the torque has decreased to 70 ounce-inches.

A torque vs. speed curve must be used in the process of selecting a stepper motor. Note that the speed must be given in steps per second, not in rpm.

7.0 STEPS PER SECOND/RPM CONVERSIONS

As previously stated in part 1.2, paragraph B, it is necessary to convert information from "rpm" into "steps per second." The following formulas may be used:

1. Converting rpm into steps per second with a 1.8° step angle, 200 step per revolution motor:
   Steps Per Second = RPM x 3.34
2. For other step angles, use the following general formula:
   Steps Per Second = (rpm) (Steps per Revolution/60)
3. To find the rpm rate when the steps per second rate is known, use the following:
   For a 1.8°, 200 step per revolution motor
   rpm = Steps Per Second/3.34



M062-LE09 Motor With 3.5 Ampere, 28 Vdc Bipolar Chopper Drive
Figure 6

8.0 HANDLING INTERTIAL LOADS (Acceleration/Deceleration Time Allowed)

Stepper Motors are not limited to a specific "maximum moment of inertia" due to their ability to be accelerated to and decelerated from any given speed.

Moving an inertial load is a function of time and torque. The more time allowed to move a particular distance, the more inertia that can be moved.

The required torque can be calculated when the total value of inertia, the time allowed to accelerate and decelerate (acceleration rate) and the step angle of the motor are known.

The following formula applies:

$Tj = (j)(\alpha)(k)$ where:

Tj = Torque required to move the inertial (oz-in)

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j = Total system inertia including inertia of motor rotor (lb-in^2)
α = Acceleration rate (steps per second^2) (time element)
k = A constant. For 1.8° step motors, the constant is 1.31 x 10^{-3}

Further defining α:

$$\alpha = \frac{\Delta V \text{ (sps)}}{\Delta T \text{ (seconds)}} \quad \frac{\text{(change in velocity)}}{\text{(change in time)}}$$

Note that increasing the ΔT factor (time) will decrease α. Inserting α into the formula, then, will decrease the torque requirement. This example clearly illustrates that, if enough time is allowed, the required torque becomes very low.

IMPORTANT: The "Tj" value in the formula is the torque required to move the **inertia** only and **does not** include the **friction** torque requirement of the system. Friction torque must be added to get the total torque requirement. For example: assume that Tj equals 35 ounce-inches and frictional torque equals 50 ounce-inches. Total torque required would be 50 + 35, or 85 ounce-inches at the speed specified. The proper motor can now be determined by consulting a torque vs. speed curve and selecting the motor which produces 85 ounce-inches at the desired speed and acceleration rates.

8.1 HANDLING INERTIAL LOADS (No Acceleration/Deceleration Time Allowed)

At stepping rates above 50 steps per second where **no** acceleration/deceleration time is allowed, the following formula may be used:

Tj = (j) (α) (k) where
Tj = Torque required to move the inertial load (oz-in)
j = Total system inertia including rotor j of motor (lb-in^2)
α = $\frac{V^2}{2} \quad \frac{(SPS)^2}{2}$
k = Constant (1.31 x 10^{-3} for a 1.8° stepper motor)

EXAMPLE: An application requires a 1.8° stepper motor to move 200 steps in one second with an inertial load of 1.5 lb-in^2. Friction torque is 25 oz-in. No acceleration/deceleration is allowed. An M092 frame size motor is desired.

Solution:

$$T = (j) \frac{(V^2)}{2} (k)$$

j = 1.5 lb-in^2 + M092 rotor j of 0.42 lb-in^2= 1.92 lb-in^2
k = 1.31 x 10^{-3} (constant)

Tj = (1.92) (200^2/2) (1.31 x 10^{-3})

Tj = (1.92) 20 x 10^3) (1.31 x 10^{-3})
Tj = 50.3 oz-in (torque required to move inertia)
+ TFriction of 25.0 oz-in

Total torque required: 75.3 oz-in @ 200 steps per second.

9.0 HOLDING TORQUE VS. TORQUE AT STANDSTILL

True holding, or "breakaway" torque is measured at **rated** voltage and current. For this reason, there is often confusion between holding torque and torque at zero steps per second with a given "drive." Typically at "standstill," a drive **does not** provide **rated** voltage and current to the motor due to a safety factor. Therefore, the standstill torque value at zero steps per second is generally less than **true** holding torque at **rated** voltage and current.

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MECHANICAL SPECIFICATIONS, 1.8° SLO-SYN STEPPER MOTORS

BASIC MOTOR SERIES	MINIMUM HOLDING TORQUE (1) OZ.-IN. (2) (Ncm) (3)	MINIMUM RESIDUAL TORQUE (2) OZ-IN. (Ncm)	NOMINAL ROTOR INERTIA OZ-IN-SEC^2 (kg-cm^2)	TYPICAL TORQUE TO INERTIA RATIO (RAD/SEC.^{2})	NUMBER OF LEADS OR TERMINALS	SHAFT DIAMETER INCHES (mm)	MAXIMUM OVERHANG LOAD LBS (kg)	MAXIMUM THRUST LOAD LBS (kg)
KM060	68 (48)	2.0 (1.4)	0.0015 (0.108)	4.41 X 10^4	4 or 6	0.250 (6.35)	15 (6.8)	25 (11.3)
KM061	170 (120)	3.0 (2.1)	0.0034 (0.24)	4.38 X 10^4	4 or 6	0.250 (6.35)	15 (6.8)	25 (11.3)
KM062	250 (177)	6.0 (4.2)	0.0056 (0.395)	5.05 X 10^4	4 or 6	0.250 (6.35)	15 (6.8)	25 (11.3)
KM063	350 (247)	7.0 (4.9)	0.0084 (0.593)	4.13 X 10^4	4 or 6	0.3125 (7.94)	15 (6.8)	25 (11.3)
M061	75 (53)	1 (0.71)	0.0017 (0.12)	4.53 X 10^4 (3)	4, 6 or 8	0.250 (6.35)	15 (6.8)	25 (11.3)
M062	125 (88)	1.4 (0.99)	0.0033 (0.23)	3.75 X 10^4 (3)	4, 6 or 8	0.250 (6.35)	15 (6.8)	25 (11.3)
KM091	385 (272)	10 (7.1)	0.0160 (1.13)	2.40 X 10^4	4 or 6	0.500 (12.70)	25 (11.3)	50 (22.7)
KM092	770 (544)	15 (11)	0.0310 (2.19)	2.52 X 10^4	4 or 6	0.500 (12.70)	25 (11.3)	50 (22.7)
KM093	1155 (816)	23 (16)		2.52 X 10^4	4 or 6	0.500 (12.700	25 (11.3)	50 (22.7)
M091	180 (127)	2 (1.41)	0.0095 (0.67)	1.87 X 10^4 (3)	4, 6 or 8	3.75 (9.53)	25 (11.3)	50 (22.7)
M092	370 (261)	3.9 (2.75)	0.0174 (1.23)	2.12 X 10^4 (3)	4, 6 or 8	0.375 (9.53)	25 (11.3)	50 (22.7)
M093	550 (388)	6.9 (4.87)	0.0265 (1.87)	2.05 X 10^4 (3)	4, 6 or 8	0.375 (9.53)	25 (11.3)	50 (22.7)
M111 MX111 (4)	850 (600)	6 (4.24)	0.0555 (3.93)	1.53 X 10^4 (3)	4, 6 or 8	0.375 (9.35)	25 (11.3)	50 (22.7)
M112-FD	1390 (981)	12 (8.47)	0.1140 (8.06)	1.21 X 10^4 (3)	4, 6 or 8	0.500 (12.7)	25 (11.3)	50 (22.7)
M112-FJ MX112 (4)	1390 (981)	12 (8.47)	0.1140 (8.06)	1.21 X 10^4 (3)	4, 6 or 8	0.625 (15.88)	25 (11.3)	50 (22.7)
MH112	1760 (1243)	85 (60)	0.1334 (9.42)	1.31 X 10^4 (3)	4 or 8	0.625 (15.88)	50 (22.7)	100 (45.4)
MH172	5330 (3764)	50 (35.3)	0.8702 (61.5)	6.1 X 10^3 (3)	4 or 8	0.75 (19.05)	100 (45.4)	150 (68)

(1) Both windings at rated current.
(2) Values shown are for reference information and are correct to the best of our knowledge at time of publication, but are subject to change without notice. Parameters to be used as part of a specification should be verified with the factory.
(3) Operation below rated current will reduce torque and may degrade step accuracy.
(4) Available only with 4 leads.

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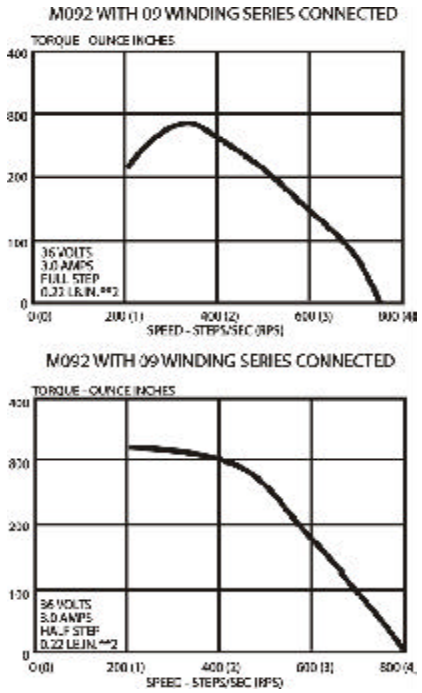
11.0 MICROSTEPPING

Microstepping is a method of step motor control that allows the rotor to be positioned at places other than the 1.8° or 0.9° locations provided by the full-step and half-step methods. Microstepping positions occur between these two angular points in the rotation of the rotor.

The most commonly used microstep increments are 1/5, 1/10, 1/16, 1/32, 1/125 and 1/250 of a full step. These increments have been chosen by Superior Electric to simplify control of both US and metric units of measurement, and also allow finer positioning resolution. While a full step of 1.8° will give a positioning resolution of 0.001 inch when the motor is driving through a lead screw that has 0.2000 inch leads, resolutions of 0.000008 inch or less are theoretically possible using microstepping.

Another major benefit of microstepping is that it reduces the amplitude of resonance that occurs when the motor is operated at its natural frequency or at sub-harmonics of that frequency. The improved step response and reduced amplitude of the natural resonances result from the finer step angle. Figure 7 shows two typical Torque vs. Speed curves. The blank area at the beginning of each curve represents the area where resonance may occur.

Selection of a Superior Electric drive which provides microstepping operation allows the user to obtain the benefits of smoother step motor performance and finer step resolution.



Typical Torque Vs. Speed Curves Showing Area of Resonance
Figure 7

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12.0 RESONANCE

When a stepper motor is operated at its no load natural frequency, which is typically 90 to 160 steps per second depending on the motor model, an increase in the audible noise and vibration levels of the motor may occur. In actual use, the frequency at which the resonance will occur can vary widely, depending on the characteristics of the load.

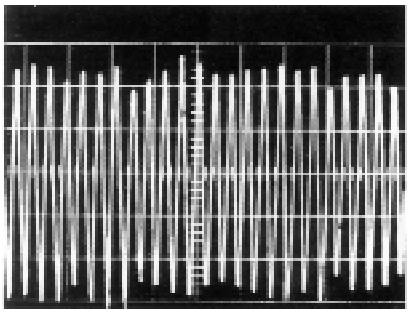
In applications where the motor must be operated at its "natural frequency," **inertial loading** (a flywheel) can be added to reduce resonance and allow satisfactory performance.

The natural frequency is **lowered** as inertia is increased. Another method is to operate at a higher stepping rate whenever possible. Also, the characteristics of the electronic drive can be changed to permit a "softer" step. However, this will result in a trade-off of torque-speed performance. Resonance can also occur at some higher harmonic of the "primary" resonant region (90 to 160 steps per second), but it is normally much less severe in these regions.

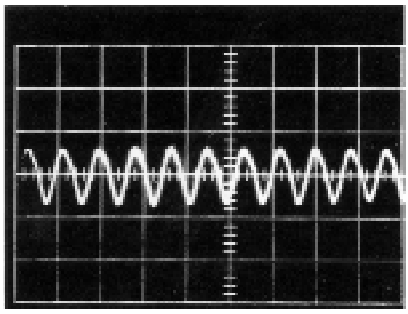
13.0 LANCHESTER DAMPERS

As discussed in Section 12.0, the effects of resonance can be reduced or eliminated by adding inertia (a flywheel) to the system. Adding inertia, however, can cause a reduction in overall system performance, especially where the friction load component is substantial.

SLO-SYN Step Motors are available with a viscous coupled inertial damper, called a Lanchester Damper. This device incorporates a light-weight aluminum outer shell which is driven by the motor shaft. A heavier flywheel located within the light-weight housing is caused to rotate by the "shear" effect of a fluid located between the outer rotating shell and the internal inertial flywheel. The results are good damping characteristics with little loss of overall performance. Figure 8 shows typical instantaneous velocity variations of an undamped motor operating in the primary resonance region while Figure 9 shows the dramatic reduction of these velocity variations when the Lanchester Damper is applied.



UNDAMPED MOTOR
FIGURE 8



DAMPED MOTOR
FIGURE 9

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14.0 ENCODER MOTORS

For those desiring an indication of true shaft position, a complete line of Encoder Motors is available. The encoder outputs produce one pulse for each step taken by the motor. Theses signals are in "phase quadrature" (two-channel output, 90° phase shift between the two channels) with one of those signals used as a reference for up and down counting. A third channel is also available as a "zero reference" or revolution counter whereby one output pulse per revolution is provided. Figure 10 shows a typical configuration and pulse output.

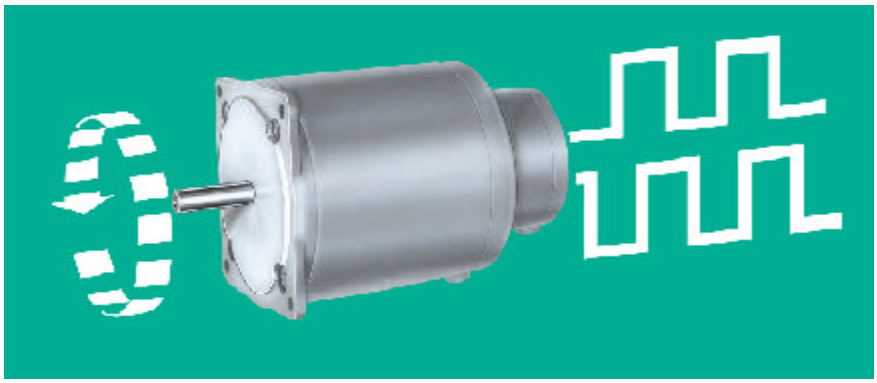


FIGURE 10

15.0 SPECIAL CAPABILITY STEPPER MOTORS

SLO-SYN Stepper Motors can be produced in a wide variety of special configurations, including:

A. **Double Ended Shaft -** Having a shaft that extends from both ends of the motor. Available in all models.

B. **Explosion-Proof -** Meet Underwriters Laboratories specifications for Class 1, Group D or Class 2, Groups E, F and G service.

C. **Special Environment -** Include High Temperature, Militarized, Limited Vacuum, Radiation Resistant and Splash-Proof models.

D. **Special Windings -** Electrical characteristics can be designed to perfectly match your drive for optimum performance.

E. **Special Shaft Configurations -** Flats, keyways, tapers, holes, knurls, threads, splines, etc. are available.

F. **Winding Configurations -** two-phase, three-phase or four-phase motors designed for single or dual winding excitation can be produced, depending on the model chosen.

For many years, Superior Electric has produced a wide variety of special motors to meet specific customer application needs. If you have a need for a "customized" stepper motor, contact us. Chances are, we've done it before!

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16.0 SELECTING A STEPPER MOTOR - INFORMATION REQUIRED

Sections 16.1, 16.2 and 16.3 which follow, provide formulas needed to calculate information required when selecting a stepper motor. Before these formulas can be used, however, it is necessary to obtain detailed information about the applications. The more complete the data, the more accurate the motor selection which will result.

The required data is as follows:

I. Clearly define the application

II. Determine the mechanical requirements

- A. Size and weight
- B. Mounting method
- C. Resolution - steps per revolution, linear increments
- D. Accuracy required - percent error
- E. Shaft Configuration - double-ended, keyway, etc.
- F. Runout
- G. Special environment capability
- H. Damper
- I. Encoder
- J. Leads or terminals
- K. Gearing, lead screws - define

III. Load Requirements

- A. Torque at standstill (power on)
- B. Torque at standstill (power off - detent)
- C. Torque at speed (running or "slew")
- D. Inertia (reflected)
- E. Distance versus time data
    1. Average speed
    2. Maximum speed

IV. Electronic drive description

- A. Type of drive
    1. Translator - pulse-to-step conversion
    2. Translator/Oscillator - Translator plus built in Oscillator
    3. Indexer - controls count, direction, etc.
- B. Source
    1. Customer built
    2. Purchased
- C. Drive design type
    1. Unipolar L/R
    2. Bipolar L/R
    3. Bi-level
    4. Constant current bipolar chopper
    5. Other - define
- D. Power supply capabilities
    1. AC input
    2. DC voltage
    3. DC current

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E. Drive Control logic
   1. Input pulse characteristics
   2. Ramping
   3. Damping
   4. Open- or closed-loop
   5. Full/half-step, microstep

16.1 SELECTING DC STEPPER MOTORS-FORMULAS

Before the correct SLO-SYN Stepper Motor for a particular application can be selected, the following information must be determined:

a) operating speed in steps per second
b) torque in ounce-inches
c) load inertia in lb-in²
d) required step angle
e) time to accelerate in milliseconds
f) time to decelerate in milliseconds
g) type of drive system to be used
h) size and weight considerations

Once this information is known, the best motor/drive combination can be determined using the torque vs. speed curves in the SLO-SYN Motors and Drives catalog and the formulas which follow.

1. Torque (oz-in) = Fr
where **F** = Force (in ounces) required to drive the load
r = Radius (in inches)

2. Moment of Inertia

$$I\ (\text{lb-in}^2) = \frac{Wr^2}{2} \quad \text{for a disk}$$

or

$$I\ (\text{lb-in}^2) = \frac{W}{2}(r_1^2 + r_2^2) \quad \text{for a cylinder}$$

Where **W** = Weight in pounds
r = Radius in inches

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3. Equivalent Inertia

A motor must be able to:

a. overcome any frictional load in the system
b. start and stop all inertial loads, including that of its own rotor

The basic rotary relationship is:

$$\mathbf{T} = I\alpha/24$$

Where **T = torque in ounce-inches**
I = moment of inertia in lb-in^2
α = angular acceleration in radians per second^2

Angular acceleration (α) is a function of the change in velocity (ω) and the time required for the change.

$$\alpha = \frac{\omega 2 - \omega 1}{t}$$

or, if starting from zero

$$\alpha = \frac{\omega}{t}$$

where ω = angular velocity in radians per second
t = time in seconds

$$\text{since } \omega = \frac{\text{steps per second}}{\text{steps per revolution}} \times 2\pi$$

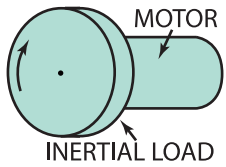
angluar velocity and angular acceleration can also be expressed in steps per second (ω^1) and steps per second^2 (α), respectively.

SAMPLE CALCULATIONS

A. Calculating torque required to rotationally accelerate an inertial load

$$\mathbf{T} = 2 \times I_0 \times \frac{\alpha^1}{t} \times \frac{\pi \text{Ø}}{180} \times \frac{1}{24}$$

where **T** = torque required in oz-in
$\mathbf{I_0}$ = inertial load in lb-in^2
$\boldsymbol{\pi}$ = 3.1416
Ø = step angle in degrees
α^1 = step rate in steps per second



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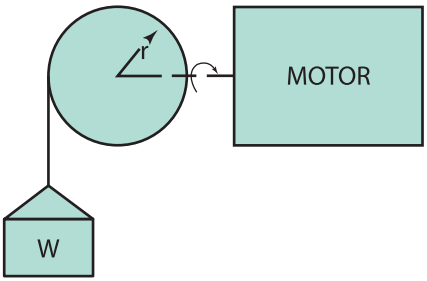
EXAMPLE: assume the following conditions:

Inertia = 9.2 lb-in2
step angle = 1.8°
acceleration = from 0 to 1000 steps per second in 0.5 seconds

$$\mathbf{T} = 2 \times 9.2 \times \frac{1000}{0.5} \times \frac{p \times 1.8}{180} \times \frac{1}{24}$$

T = 48.2 oz-in torque required to

B. Calculating torque required to accelerate and raise a weight using a drum and string.



The total torque which the motor must supply includes the torque required to:

- **a.** accelerate the weight
- **b.** accelerate the drum
- **c.** accelerate the motor rotor
- **d.** lift the weight

The rotational equivalent of the weight and the radius of the drum is:

$$\mathbf{I}_{(eq)} = wr^2$$

where $\mathbf{I}_{(eq)}$ = equivalent inertia in lb-in^2
w = weight in lbs
r = radius of drum in inches

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EXAMPLE: Assume the following conditions

Weight	5 lbs (80 oz)
Drum	3 inches O.D., 1.5 inches radius
Velocity	15 ft per second
Time To Reach Velocity	0.5 second
Motor Rotor Inertia	2.5 lb-in^2
Drum Inertia	(3" dia x 2" lg., steel) 4-5 lb-in^2

$$\begin{array}{lcll} \mathbf{I}_{(eq)} & = & 5 \times (1.5)2 & = & 11.25 \text{ lb-in}^2 \\ & & \text{I (drum)} & = & 4.50 \text{ lb-in} \\ & & \underline{\text{I (rotor)}} & = & \underline{2.50 \text{ lb-in}} \\ & & \text{I (total)} & = & 18.25 \text{ lb-in}^2 \end{array}$$

since the velocity is 15 ft per second using a 3" drum, the velocity in rev. per second can be calculated.

$$\text{speed} = \frac{15 \times 12}{3 \times \pi} = 19.1 \text{ rev per second}$$

The motor step angle is 1.8°, or 200 steps per revolution.

Therefore:

$$\omega' = 19.1 \times 200 = 3820 \text{ steps per second}$$

$$\mathbf{T} = 2 \times I_0 \times \frac{\omega'}{t} \times \frac{\pi \times \text{Ø}}{180} \times \frac{1}{24}$$

$$\mathbf{T} = 2 \times 18.25 \times \frac{3820}{0.5} \times \frac{3.1416 \times 1.8}{180} \times \frac{1}{24}$$

$$\mathbf{T} = 364 \text{ oz-in} = \text{torque required to accelerate the system}$$

Torque required to lift the weight equals

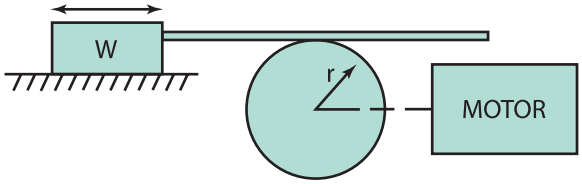
$$\begin{array}{lcl} \mathbf{T} & = & wr \\ & = & 80 \times 1.5 \\ & = & 120 \text{ oz-in} \end{array}$$

total torque required is, therefore:

364 oz-in (torque to accelerate)
120 oz-in (lifting torque)
484 oz-in (total torque)

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C Calculating the torque required to accelerate a mass moving horizontally and driven by a rack and pinion or similar device.



The total torque which the motor must provide includes the torque required to:

a. accelerate the weight, including that of the rack
b. accelerate the gear
c. accelerate the motor rotor
d. overcome the frictional losses

to calculate the rotational equivalent of the weight:

$$I_{(eq)} = w\,r^2$$

where w = weight in lbs
r = radius in inches

EXAMPLE

assume:

weight	=	5 lb
gear pitch diameter	=	3 inches
gear radius	=	1.5 inches
velocity	=	15 feet per second
time to reach velocity	=	0.5 second
pinion inertia	=	4.5 lb-in2
motor rotor inertia	=	2.5 lb-in2

$I_{(eq)}$	=	$w\,r^2$	=	$5 \times (1.5)^2$	=	11.25 lb-in^2
				I pinion	=	4.5 lb-in^2
				I rotor	=	2.5 lb-in^2
				I total	=	18.25 lb-in^2

Velocity is 15 feet per second with a 3" pitch diameter gear.

Therefore:

$$\text{Speed} = \frac{15 \times 12}{3 \times \pi} = 19.1 \text{ rev. per second}$$

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The motor step angle is 1.8° (200 steps per revolution). Therefore, the velocity in steps per second is:

$$w = 19.1 \times 200 = 3820 \text{ steps per second}$$

To calculate the torque needed to accelerate the system:

$$\mathbf{T} = 2 \times I_0 \times \frac{\omega'}{t} \times \frac{\pi Ø}{180} \times \frac{1}{24}$$

$$\mathbf{T} = 2 \times 18.25 \times \frac{3820}{0.5} \times \frac{3.1416 \times 1.8}{180} \times \frac{1}{24}$$

$$\mathbf{T} = 364 \text{ oz-in}$$

To calculate torque needed to slide the weight, assume a frictional force of 6 oz.

$$T \text{ friction} = 6 \times 1.5 = 9 \text{ oz-in}$$

Total torque required = 364 oz-in
+ 9 oz-in
= 373 oz-in

Lead Screw Formulas and Sample Calculations

1. Linear Speed

$$\text{Linear Speed (ipm)} = \frac{\text{steps/sec.}}{\text{steps/rev.}} \times 60 \times \frac{1}{p}$$

where **p** = lead screw pitch (threads per inch)

2. Axial Force

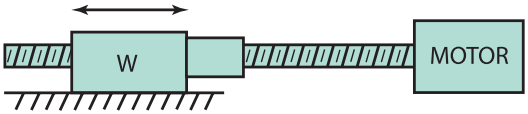
$$\text{Force (lb)} = \frac{2\pi}{16} \times T \times p \times \text{eff.}$$

Where **T** = torque in oz-in
p = lead screw pitch (threads per inch)
eff. = lead screw efficiency expressed as a decimal: 90% = 0.90

Note: Ball-nut lead screws are generally 85% to 95% efficient. Acme screws are generally 35% to 45% efficient, but can be as high as 85%.

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A. Calculating the torque required to accelerate a mass moving horizontally and driven by a ball bearing lead screw and nut.



The total torque the motor must provide includes the torque required to:

a. accelerate the weight
b. accelerate the lead screw
c. accelerate the motor rotor
d. overcome the frictional force

to calculate the rotational equivalent of weight **w:**

$$I_{(eq)} = w \times \frac{1}{p^2} \times (1/2\pi)^2$$

where **w** = weight
p = pitch in threads per inch
$\mathbf{I_{(eq)}}$ = equivalent polar inertial in lb-in^2

to calculate lead screw inertia (steel screw)

$$I\ screw = D^4 \times length \times 0.028$$

EXAMPLE

weight	=	100 lb
velocity	=	0.15 ft per second
time to reach velocity	=	0.1 second
ball screw diameter	=	1.5 inches
ball screw length	=	48 inches
ball screw pitch	=	5 threads per inch
motor rotor inertia	=	2.5 lb-in2
friction force to slide weight	=	6 oz.

$$I_{(eq)} = w \times \frac{1}{p^2} \times 0.025$$

$$I_{(eq)} = 1000 \times \frac{1}{25} \times 0.025$$

$I_{(eq)}$ = 1.0 lb-in2

I (screw)	=	D^4 x length x 0.028
I (screw)	=	5.06 x 48 x 0.028
I (screw)	=	6.8 lb-in2
I (screw)	=	6.8 lb-in2
$I_{(eq)}$	=	1.0
I rotor	=	2.5 lb-in2
I total	=	10.3 lb-in

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Velocity is 0.15 feet per second, which is equal to 1800 steps per second (the motor steps in 1.8° increments).

Torque to accelerate system

$$T = 2 \times I_0 \times \frac{\omega'}{t} \times \frac{3.14146 \times 1.8}{180} \times \frac{1}{24}$$

$$T = 2 \times 10.3 \times \frac{1800}{0.1} \times \frac{3.1416 \times 1.8}{180} \times \frac{1}{24}$$

$$T = 484 \text{ oz-in}$$

Torque to overcome friction

$$F = 0.393 \times T \times p \times \text{eff.}$$

$$6/16 = 0.393 \times T \times 0.90$$

where F = frictional force in lb-in
T = torque in oz-in
p = lead screw pitch in threads per inch
T = 0.22 oz-in

Total torque required = 0.22 oz-in
484.00 oz-in
484.22 oz-in

CONVERSION FACTORS

INERTIA

slug-ft^2 x 4600	=	lb-in^2
lb-ft^2 x 144	=	lb-in^2
oz-in^2 x 0.0625	=	lb-in^2
lb-ft-sec^2 x 4600	=	lb-in^2
lb-ft-sec^2 x 384	=	lb-in^2
oz-in-sec^2 x 24	=	lb-in^2
gm-cm^2 x 0.000342	=	lb-in^2
kp-m-sec^2 x 33,500	=	lb-in^2

METRIC - DECIMAL EQUIVALENTS

1 inch	=	2.54 cm
1 cm	=	0.3937 inch
1 pond (gm)	=	0.03527 oz.
1 oz	=	28.35 pond (gm)
1 kp (kg)	=	2.205 pound
1 gm-cm	=	0.0139 oz-in
1 kg-cm	=	1 kp-cm = 13.9 oz-in
1 hp	=	746 watts

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16.2 SELECTING DC STEPPER MOTORS-INCH UNITS

The following information will serve to amplify the application data given previously.

1) The torque required to accelerate a mass rotationally is found from the fundamental relationship that Torque = moment of inertia times angular acceleration $T = I_0 \alpha$.

This is a relation based on the rotational mass. Gravitational units, such as pound-inches squared, must be converted into mass units by applying the gravitational constant. This constant is 32.2 feet per second squared, which has been rounded to 32 feet per second squared for our use. As an illustration, assume an inertia of 9.2 lb-in^2.

$9.2 \times 16 = 147.2$ oz-in^2

Gravitational constant (g) = 32 ft per sec^2

$g = 32 \times 12 = 384$ in. per sec^2

The moment of inertia in **mass** units and in **compatible** units, therefore, is:

$$I_0 \text{ (oz-in sec}^2) = \frac{I_0 \text{ (lb-in}^2) \times 16}{g \text{ (in/sec}^2)}$$

$$= I_0 \text{ (lb-in}^2) \times \frac{16}{384}$$

$$= I_0 \text{ (lb-in}^2) \times \frac{1}{24}$$

$$9.2 \text{ lb-in}^2 = 9.2 \times \frac{1}{24} \text{ oz-in-sec}^2 = 0.383 \text{ oz-in-sec}^2$$

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2) Angular acceleration alpha (α) in the expression $T - I_0 \alpha$ is in units of radians per second squared, α = rad/sec^2. A circle (360°) contains 2 pi radians, 360° - 2π radians, or one radian = 57.3 degrees (approximately). Acceleration is the change of velocity per unit of time. In the rotational case being considered, velocity is expressed in radians per second and is denoted by ω (omega). The angular velocity for a stepper motor is therefore equal to the stepping rate (steps per second) times the step angle in radians.

$$\text{Step angle (radians)} = \text{step angle (degrees)} \times \frac{2\pi}{360}$$

Assume a 200 step per revolution (1.8° per step) motor running at 1000 steps per second.

$$w = 1000 \times 1.8 \times \frac{2\pi}{360}$$

$$= 31.42 \text{ radians per second}$$

The angular acceleration, α is the rate of change of angular velocity per unit of time (seconds). If the change is from zero speed, or velocity, the angular acceleration is the final angular velocity (ω_2) divided by the time taken to reach that velocity.

Assume the above motor reaches the speed of 1000 steps per second in 0.5 second. The angular velocity is:

$$\alpha = \frac{\omega_2}{t} = \frac{31.42}{0.5} = 62.84 \text{ rad. per sec}^2$$

If the change of velocity is from a first speed (ω_1) to a second speed (ω_2), the acceleration is:

$$\alpha = \frac{\omega_2 - \omega_1}{t}$$

To obtain the acceleration torque in oz-in, the inertia must be expressed in oz-in-sec^2 and the acceleration in radians/sec^2.

3) To accelerate an inertia of 9.2 lb-in^2 to 1000 steps per second in 0.5 second requires what torque?

$$T = I_0 \text{ (oz-in-sec2)} \times \text{(rad/sec}^2\text{)}$$
$$= 0.383 \times 62.84$$
$$= 24.1 \text{ oz-in}$$

4) For 1.8° per step (200 step per revolution) motors, this may be restated as:

$$T \text{ (oz-in)} = I_0 \text{(lb-in}^2\text{)} \times \frac{\text{change in speed (steps per second)}}{\text{time for change (seconds)}} \times \frac{1.8 \times \pi}{24 \times 360}$$

$$= I_0 \times \frac{\Delta s}{\Delta t} \times 1.31 \times 10^{-3}$$

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16.3 SELECTING DC STEPPER MOTORS - METRIC UNITS

1) The torque required to accelerate a mass rotationally is found from the fundamental relationship that Torque = moment of inertia times angular acceleration: $T = I_0 \ \alpha$

This is a relationship based on the rotational mass. Gravitational units, such as kg-cm squared, must be converted into mass units by applying the gravitational constant. This constant is 981 cm/sec squared, which has been rounded off to 980 cm/second squared for our use. As an example, assume an inertia of 26.9 kg-cm^2.

Gravitational constant is 980 cm/sec^2

The moment of inertia in **mass** units and in **compatible** units, therefore, is:

$$I_0 \text{ (kg-cm-sec}^2\text{)} = \frac{I_0 \text{ (kg-cm}^2\text{)}}{g \text{ (cm/sec}^2\text{)}}$$

$$= I \text{ (kg-cm}^2\text{)} \times \frac{1}{980}$$

$$26.9 \text{ kg-cm}^2 \times \frac{1}{980} = 0.027 \text{ kg-cm-sec}^2$$

2) Angular acceleration alpha (α) in the expression $T=I_0 \ \alpha$ is in units of radians per second squared.

A circle (360°) contains 2 pi radians: 360° = 2π radians, or one radian = 57.3 degrees (approximately). Acceleration is the change of velocity per unit of time. In the rotational case being considered, velocity is expressed in radians per second and is denoted by ω (omega). The angular velocity for a stepper motor is therefore equal to the stepping rate (in steps per second) times the step angle (in radians).

$$\text{Step Angle (radians)} = \text{step angle (degrees)} \times \frac{2\pi}{360}$$

Assume a 200 step per revolution (1.8° step angle) motor running at 1000 steps per second.

$$\omega = 1000 \times 1.8 \times \frac{2\pi}{360}$$

$$= 31.42 \text{ radians per second}$$

The angular acceleration (a) is the change of velocity per unit of time (seconds). If the change is from zero speed or velocity, the angular acceleration is the angular velocity (ω_2) divided by the time taken to reach that velocity.

Assume the above motor reaches the speed of 1000 steps per second in 0.5 second. The angular velocity is: ω_2 = 31.42 radians per second.

$$\alpha = \frac{\omega_2}{t} = \frac{31.42}{0.5} = 62.84 \text{ radians per second}^2$$

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If the change in velocity is from first speed (ω_1) to a second speed (ω_2), the acceleration is:

$$\alpha = \frac{\omega_2 - \omega_2}{t}$$

To obtain the acceleration torque in kg-cm, the inertia must be kb-cm-sec^2.

3) What torque is required to accelerate an inertia of 26.9 kg-cm^2 to 1000 steps per second in 0.5 second?

$$T = I_0 \text{ (kg-cm-sec}^2\text{)} \times \text{rad/sec}^2$$

$$= 0.027 \times 62.84$$

$$= 1.7 \text{ kg-cm}$$

4) For 1.8° per step (200 steps per revolution) motors, this may be restated as:

$$T \text{ (kg-cm2)} = I_0 \times \frac{\text{change in speed (steps/sec}}{\text{time for change (seconds)}} \times \frac{1}{980} \times \frac{1.8 \times 2\pi}{360}$$

$$= I_0 \text{ (kg-cm}^2\text{)} \times \frac{\Delta s}{\Delta t} \times 3.2 \times 10^{-5}$$

$$T = 26.9 \times \frac{1000}{0.5} \times 3.2 \times 10^{-5}$$

$$= 1.72 \text{ kg-cm}$$

17.0 APPLICATIONS

The applications for SLO-SYN Stepper Motors are virtually unlimited. Listed are some typical applications where reliability, repeatability and controllability are most important.

APPLICATION	USE
Computer Peripherals	
Floppy Disc	position magnetic pickup
Printer	carriage drive
Printer	rotate character wheel
Printer	paper feed
Printer	ribbon wind/rewind
Printer	position matrix print head
Tape Reader	index tape
Plotter	X-Y-Z positioning
Plotter	paper feed

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APPLICATION	USE
Business Machines	
Card Reader	position cards
Copy Machine	paper feed
Banking Systems	credit card positioning
Banking Systems	paper feed
Typewriters (automatic)	head positioning
Typewriters (automatic)	paper feed
Copy Machine	lens positioning
Card Sorter	route card flow
Process Control	
Carburetor Adjusting	air-fuel mixture adjust
Valve Control	fluid gas metering
Conveyor	main drive
In-Process Gaging	parts positioning
Assembly Lines	parts positioning
Silicon Processing	I.C. wafer slicing
I.C. Bonding	chip positioning
Laser Trimming	X-Y positioning
Liquid Gasket Dispensing	valve cover positioning
Mail Handling System	feeding and positioning letters
Machine Tool	
Milling Machines	X-Y-Z table positioning
Drilling Machines	X-Y table positioning
Grinding Machines	downfeed grinding wheel
Grinding Machines	automatic wheel dressing
Electron Beam Welder	X-Y-Z positioning
Laser Cutting	X-Y-Z positioning
Lathes	X-Y positioning
Sewing	X-Y table positioning
Graphics	
Printing Presses	roller drive
Printing Presses	ink pump
Phototypesetting Equipment	rotate character wheel and paper feed
Film Processing	index film frame-by-frame
Animation Camera	control focus, fade, dissolve, etc.
Microfilm Systems	position film
Microfilm Systems	automatic focus
Medical	
I.V. Pump	control drip plate
X-Ray Equipment	scanning head positioning
X-Ray Equipment	position patient
Blood Analyzer	test tube positioning
Radiation Therapy	scanning head positioning

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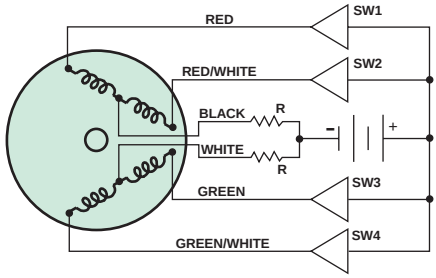
18.0 THE ELECTRONIC DRIVE

The most important element in any stepper motor system is the electronic drive which controls the motor.

The "drive" determines the performance characteristics of a given motor. Parameters such as speed, time for a single step, holding torque and setting time can be controlled by the electronic drive.

18.1 L/R UNIPOLAR DRIVES

This is the simplest form of stepper motor control. It has a single-ended power supply, winding sequence logic, and series resistance between drive and motor, and provides good performance to 2000 steps per second. Other advantages include high reliability and low cost.



L/R Unipolar Drive
FIGURE 11

18.2 L/R BIPOLAR DRIVES

This type of drive requires two power supplies of equal current capability. They provide good intermediate speed performance (2k to 5k sps). They energize all windings simultaneously to achieve a 30% to 40% increase over unipolar L/R drives in low speed torque. An L/R bipolar drive requires a four-lead or an eight-lead stepper motor.

18.3 TWO LEVEL DRIVES

These drives utilize two power supplies to achieve fast current rise to initiate the step and to sustain the current during the entire move. They are well suited for applications requiring short, fast moves and provide good intermediate speed performance.

18.4 REACTIVE DRIVES

A reactive drive uses a choke on the input of the power supply. This allows voltage to increase as the stepping rate is increased. No series resistor is required. This type of drive provides good overall performance. It is more expensive than an L/R drive, but is more efficient.

18.5 CHOPPER DRIVES

This is a more complex drive that "chops" the current to achieve current limiting. High voltage that can be many times the rated voltage of the motor can be applied. These drives provide good overall performance and fast response, but are expensive.

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19.0 TRANSLATORS

SLO-SYN Translators serve as the interface between a pulse source and the stepper motor. They contain the logic necessary to convert, or "translate" digital information into motor shaft rotation. The motor will move one step for each pulse received by the Translator.

The pulse source supplies the desired number of pulses at the specified or programmed rate, which provides the distance and speed information. Figure 12 shows this concept.



TRANSLATOR DRIVE SYSTEM
FIGURE 12

Some Translators can operate in an eight-step switching sequence (half-stepping). When this mode is used, one pulse input will cause the motor shaft to rotate one-half its normal distance. A 1.8° step angle motor will operate in steps of 0.9° in the half-step mode.

SLO-SYN Translators are available in both modular and packaged models in a wide range of power ratings. Modular models require an external power supply. Packaged versions are self-contained and have internal power supplies.

SLO-SYN Translator/Oscillators are also offered. Essentially, a Translator/Oscillator is a Translator with the addition of a built-in oscillator which may be used to provide the pulse and direction signals.

20.0 INDEXERS

A SLO-SYN Indexer is a complete stepper motor control package which provides control of:

- Speed (steps per second)
- Distance (number of steps per move)
- Direction (CW or CCW)

Both Preset Indexer and Programmable Indexer models are available. A SLO-SYN Preset Indexer is intended for control of simple, repetitive operations. It is used where an operation can be directed using a single line of data.

A SLO-SYN Programmable Indexer can store up to 400 lines of program information. They are designed for simplicity of programming and operation. Both modular and packaged models are offered.

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20.0 THE DRIVE SELECTION PROCESS

Follow the procedure below to select the correct motor and drive combination for your application.

A. Select the step angle which will provide the desired linear resolution.
B. Select the type of drive - Translator, Translator/Oscillator, Preset Indexer or Programmable Indexer.
C. Select the specific drive that provides the speed range required.
D. Consult the literature which gives torque vs. speed curves for the selected drive used with appropriate motors.
E. Select the motor which provides the necessary step angle and torque at the required step rate.

EXAMPLE

An X-Y table must be positioned at a rate of 255 inches per minute (4.25 inches per second). The table is positioned by a 5-pitch ball nut lead screw. Linear resolution of 0.001 inch per motor step is required. The required torque is 51 ounce-inches, including the torque needed to accelerate the inertia. It is desired to have the motor drive the table a pre-selected distance each time a "Start" command is given.

Solution

A. Select the required motor step angle needed to achieve the correct linear resolution. In this case, a 1.8°, 200 step per revolution stepper will provide the desired 0.001 inch linear motion per motor step when operating a 5-pitch (five revolutions = 1 inch linear motion) lead screw.
B. Counting capability with the ability to store a single line of program information is needed. Therefore, a Preset Indexer should be selected.
C. The required speed is 4250 steps per second (5-pitch lead screw, 1000 steps = 1" linear motion; 4.25 inches/sec required = 4250 steps per second).
D. Consult the torque vs. speed curves in the SLO-SYN Motion Control catalog and select a Motor/Indexer combination that drive the load at the required step rate.

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