BALDOR

Selecting Motion Control

Technical Reference

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Selecting Motion Control

Introduction

In the world of motion control, there are many devices – from motors to controls to positioners... Industry productivity requirements are pushing toward more efficient, effective, and faster production rates. Machines are being analyzed and upgraded to accomplish this. Repetitive tasks are automated for precision and throughput.

In selecting a motion control package, the load is being positioned rapidly and accurately, and therefore the load becomes important. Once the load is known, the torque is known; the selection of a motor which will deliver that torque can begin. Finally, the control which will supply the power to move the motor and the machine's load can be determined.

In the following presentation is a step–by–step procedure that outlines the equations to determine torques required for your motion control application.

Mechanics Of A Load

In selecting a motion control package, the first quantity that must be defined is the mechanics of the load to be moved. Once this physical data is obtained, the proper matching of motor and control can easily begin. The mechanics of the load involve both friction (which is easy to understand) and inertia (which is an unknown, since we have difficulty in recalling the physics we had in school).

Friction

The first part of the equation, determining friction of the load, can be accomplished by either estimating, or measuring by simply using a torque wrench.

Inertia

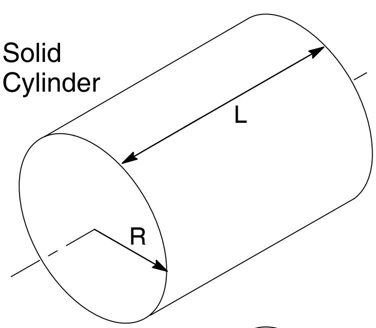
The second part is determining the inertia. Inertia is the resistance of an object to be accelerated, or decelerated. In motion control, inertia is an important parameter since it defines the torque required to accelerate the load and get it into position. If the inertia is unknown, then you must calculate the inertia.

To determine the inertia, the mechanical linkage system (that moves the load) will be analyzed. These mechanical systems can be divided into four basic categories: direct drive, gear drive, tangential drive, and leadscrew drive.

In the following, each of these mechanical linkage categories and relevant formulas for calculating the load parameters will be presented. In all instances, the formulas reflect the load parameters as "seen" by the motor. Reflecting all these parameters back to the motor shaft make the calculation easier for selecting the motor and control for your motion control application.

Figure 1 Inertia Of A Cylinder

Solid Cylinder



Where:
J = inertia (lb–in–s^2)
W = weight (lb)
R = radius (inch)
g = gravitational constant (386 in/s^2)
L = length (inch)
ρ = density (lb/in^3)

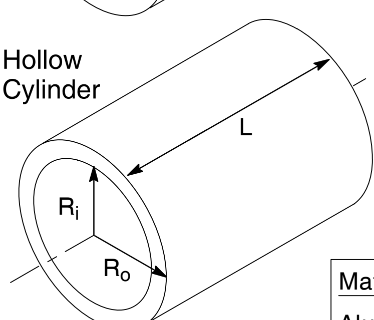
For a known weight and radius:

$$J = \left(\frac{1}{2}\right)\left(\frac{W R^2}{g}\right)$$

For a known density, radius and length:

$$J = \left(\frac{1}{2}\right)\left(\frac{\pi \; L_\rho \, R^4}{g}\right)$$

Hollow Cylinder



Where:
J = inertia (lb–in–s^2)
W = weight (lb)
R_o = outer radius (inch)
R_i = inner radius (inch)
g = gravitational constant (386 in/s^2)
L = length (inch)
ρ = density (lb/in^3)

For a known weight and radius:

$$J = \left(\frac{1}{2}\right)\left(\frac{W}{g}\right)\left(R_o^{\,2} + R_i^{\,2}\right)$$

For a known density, radius and length:

$$J = \left(\frac{1}{2}\right)\left(\frac{\pi \, L_\rho}{g}\right)\left(R_o^{\,4} - R_i^{\,4}\right)$$

Material	Density (lb/in^3)
Aluminum	0.096
Copper	0.322
Plastic	0.040
Steel	0.280
Wood	0.029

Inertia Of A Cylinder

Figure 1, shows the formulas for calculating the inertia of a cylinder. The inertia of a cylinder can be calculated if either the weight and radius are known; or the density, radius, and length are known. As an example, if the cylinder were a lead screw with a radius of .312 inches and a length of 22 inches, then the inertia is:

$$J = \left(\frac{1}{2}\right)\left(\frac{\pi \ L_\rho \ R^4}{g}\right) = \left(\frac{1}{2}\right)\left(\frac{\pi \ (22)\ (0.28)\ (0.312)^4}{386}\right) = 0.000237 \ \text{lb–in–s}^2$$

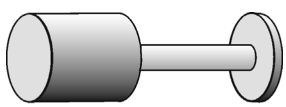
These equations are important since the inertia of mechanical components (i.e. shafts, gears, drive rollers, leadscrews, etc.) can be calculated by using them. Once the inertia is determined, it becomes just a task of reflecting that load inertia and friction through the mechanical linkages to what the motor will "see".

Mechanical Systems

Mechanical systems are divided into four basic categories: direct drive, gear drive, tangential drive, and leadscrew drive.

Direct Drive The most simple of systems is the direct drive. This would not require the load parameters to be reflected back, since there are no mechanical linkages involved. The equations for the direct drive are presented in Figure 2. The speed of the load is the same as the motor, the friction of the load is the friction which the motor must overcome, and the load inertia is directly what the motor would "see".

Figure 2 Direct Drive System Calculations



Where:
- S_m = Motor speed, RPM
- S_l = Load speed, RPM
- T_m = Motor torque, lb–in
- T_l = Load Torque, lb–in
- J_t = Total inertia, lb–in–s^2
- J_l = Load inertia, lb–in–s^2
- J_m = Motor inertia, lb–in–s^2

Motor Speed = Load Speed
$S_m = S_l$

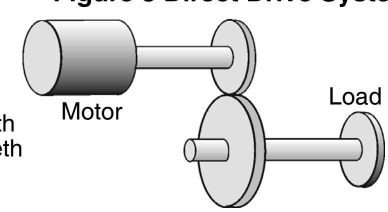
Motor Torque = Load Torque
$T_m = T_l$

Total inertia = Load inertia + Motor inertia
$J_t = J_l + J_m$

Gear Drive The mechanical linkage between the load and motor in a gear drive, Figure 3, requires reflecting the load parameters back to the motor shaft. The load inertia reflected back to the motor is a squared function of the gear ratio.

Figure 3 Direct Drive System Calculations

Where:
- S_m = Motor speed, RPM
- S_l = Load speed, RPM
- N = Gear ratio
- N_l = Number of Load Gear Teeth
- N_m = Number of Motor Gear Teeth
- T_m = Motor torque, lb–in
- T_l = Load Torque, lb–in
- e = Efficiency
- J_t = Total inertia, lb–in–s^2
- J_l = Load inertia, lb–in–s^2
- J_m = Motor inertia, lb–in–s^2



Motor Speed = Load Speed x Gear Ratio
$S_m = S_l \times N = S_l \times (N_l / N_m)$

Motor Torque = Load Torque / Gear Ratio
$T_m = T_l / N = T_l / (N_l / N_m)$

Total inertia = (Load inertia / Gear Ratio^2) + Motor inertia

$$J_t = \frac{J_l}{N^2} + J_m$$

As an example, calculate the reflected inertia for a 6 pound, solid cylinder with a 4 in. diameter, connected through a 3:1 gear. FIrst calculate the inertia of the cylinder.

$$J_l = \frac{WR^2}{2g} = \frac{6 \times (2)^2}{2 \times 386} = 0.031 \ \text{lb–in–s}^2$$

Next, reflect this inertia through the gear to the motor.

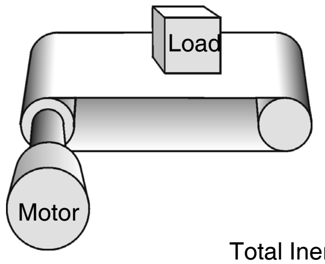
$$J_r = \frac{J_l}{N^2} = \frac{0.031}{3^2} = 0.0034 \ \text{lb–in–s}^2$$

For accuracy, the inertia of the gears should be included when determining total inertia. This value can be obtained from literature or calculated using the equations for the inertia of a cylinder. Gearing efficiency should also be considered when calculating required torque values.

Tangential Drive

A tangential drive can use a timing belt and pulley, chain and sprocket, or rack and pinion. A tangential drive is shown in Figure 4, and this drive also requires reflecting load parameters back to the motor shaft.

Figure 4 Tangential Drive System Calculations



Where:
S_m = Motor speed, RPM
V_l = Load speed, in/min
F_f = Friction force, lb
T_f = Friction Torque, lb–in
J_t = Total inertia, lb–in–s^2
J_l = Load inertia, lb–in–s^2
J_p = Pulley inertia, lb–in–s^2
J_m = Motor inertia, lb–in–s^2
g = Gravitational constant (386 in/s^2)
R = Radius, inches
W =Weight

$$\text{Motor Speed} = \frac{1}{2\pi} \times \frac{\text{Load Speed}}{\text{Radius}}$$

$$S_m = \frac{1}{2\pi} \times \frac{V_l}{R}$$

$$\text{Load Torque} = \text{Load Force} \times \text{Radius}$$

$$T_f = F_f \times R$$

$$\text{Total Inertia} = \left[\frac{(\text{Weight} \times \text{Radius}^2)}{g}\right] + \text{inertia (pulleys)} + \text{inertia (motor)}$$

$$J_t = \frac{WR^2}{g} + J_{p1} + J_{p2} + J_m$$

Example: A belt and pulley arrangement will be moving a weight of 10 lb. The pulleys are hollow cylinders, 5 lb each, with an outer radius of 2.5 in. and an inner radius of 2.3 in.
Calculate inertia for a hollow cylinder pulley:

$$J_p = \frac{1}{2}\frac{W}{g}(R_0^{\,2} + R_i^{\,2}) = \frac{1}{2}\frac{5}{386}(2.5^2 + 2.3^2) = 0.0747 \text{ lb–in–s}^2$$

Calculate load inertia:

$$J_l = \frac{WR^2}{g} = \frac{10(2.5)^2}{386} = 0.1619 \text{ lb– in – s}^2$$

Total inertia reflected to the motor shaft is the sum of the load inertia plus the two pulley inertias:

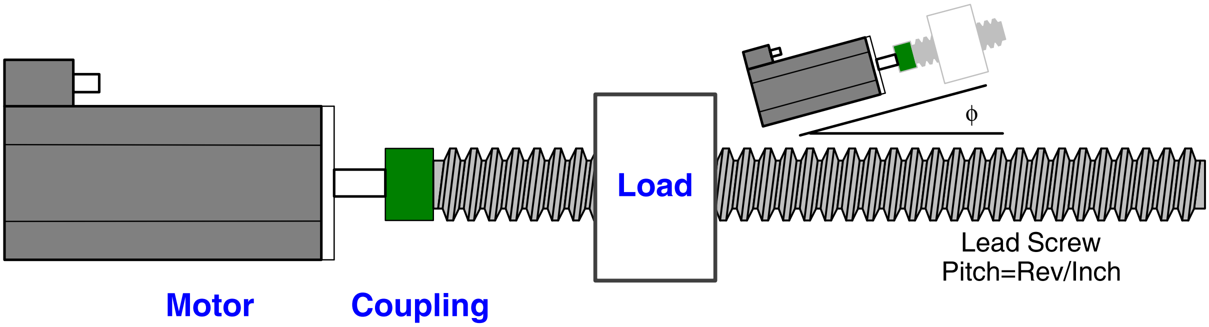
$$J = J_l + J_{p_1} + J_{p_2} = 0.1619 + 0.0747 + 0.0747 = 0.3113 \text{ lb–in–s}^2$$

Also, the inertia of pulleys, sprockets or pinion gears must be included to determine the total inertia.

Leadscrew Drive

Illustrated in Figure 5, a leadscrew drive also requires reflecting the load parameters back to the motor. Both the leadscrew and the load inertia have to be considered. If leadscrew inertia is not readily available, the equation for a cylinder may be used. For precision positioning, the leadscrew may be preloaded to eliminate or reduce backlash. Such preload torque can be significant and must be included, as must leadscrew efficiency, when calculating required torque values.

Figure 5 Leadscrew Drive System Calculations



Where:

S_m = Motor speed, RPM
V_l = Load speed, in/min
F_f = Friction force, lb
F_l = Load force, lb
F_{pl} = Preload force, lb
T_f = Friction Torque, lb–in
T_l = Torque reflected to motor, lb–in
J_t = Total inertia, lb–in–s^2
J_l = Load inertia, lb–in–s^2
J_{ls} = Leadscrew inertia, lb–in–s^2
J_m = Motor inertia, lb–in–s^2
e = Efficiency
g = Gravitational constant (386 in/s^2)
P = Pitch, rev/inch
W =Weight of Load + Table, lb
μ = coefficient of friction

Motor Speed = Load Speed x Pitch

$$S_m = V_l \times P$$

Find the Load Torque reflected to motor T_l

$$T_l = \frac{1}{2\pi}\,\frac{\text{Load Force}}{\text{Pitch x eff}} + \frac{1}{2\pi}\,\frac{\text{Preload Force}}{\text{Pitch}} \times 0.2 + \frac{1}{2\pi}\,\frac{\text{Friction Force}}{\text{Pitch x efficiency}}$$

$$T_l = \frac{1}{2\pi}\,\frac{F_l}{P \times e} + \frac{1}{2\pi}\,\frac{F_{pl}}{P} \times 0.2 + \frac{1}{2\pi}\,\frac{F_f}{P \times e}$$

Where : $F_f = \mu \times W \times \cos\phi + W \sin\phi$

$$\text{Total inertia } J_t = \frac{\text{Load}}{\text{Gravity}}\left(\frac{1}{2\pi \times \text{Pitch}}\right)^2 + \text{Leadscrew inertia} + \text{Motor inertia}$$

$$J_t = \frac{W}{g}\left(\frac{1}{2\,\pi\,P}\right)^2 + J_{ls} + J_m$$

Type	Efficiency
Ball nut	0.90
ACME (plastic nut)	0.65
ACME (metal nut)	0.40

Material	Coefficient of Friction
Steel on steel (dry)	0.58
Steel on steel (lubricated)	0.15
Teflon on steel	0.04
Ball bushing	0.003

Example: A 200 lb load is positioned by a 44 in. long leadscrew with a 0.5 in. radius and a 5 rev/in. pitch. The reflected load inertia is:

$$J_l = \frac{W}{g}\left(\frac{1}{2\pi P}\right)^2 = \frac{200}{386}\left(\frac{1}{2\pi 5}\right)^2 = 0.00052 \text{ lb–in–s}^2$$

Leadscrew inertia is based on the equation for inertia of a cylinder:

$$J_{ls} = \frac{\pi L \rho R^4}{2g} = \frac{\pi \times 44 \times 0.28 \times 0.5^4}{2 \times 386} = 0.00313 \text{ lb–in–s}^2$$

Total inertia to be connected to the motor shaft is:

$$J = J_l + J_{ls} = 0.00052 + 0.00313 = 0.00365 \text{ lb–in–s}^2$$

For precision positioning applications, the leadscrew is sometimes preloaded to eliminate or reduce backlash. If preloading is used, the preload torque must be included since it can be significant. The leadscrew’s efficiency must also be considered when finally determining torques.

The Motion Control Package

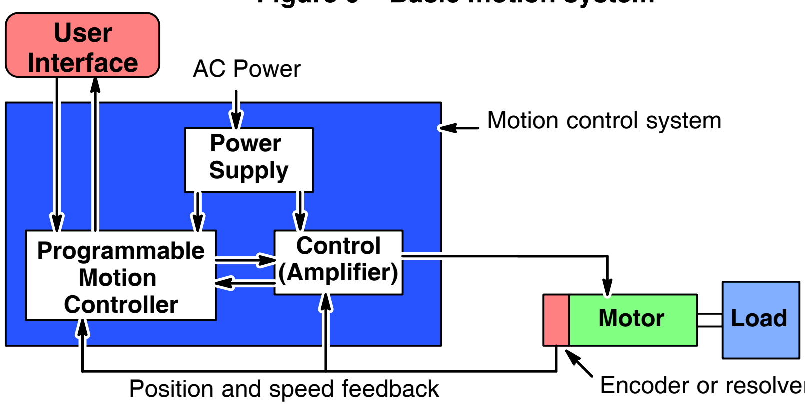
After the mechanics of the application have been analyzed, and the friction and inertia of the load are known, the next step is to determine the torque levels required. Then, a motor can be sized to deliver the required torque and the control sized to power the motor. If friction and inertia are not properly determined, the motion system will either take too long to position the load, it will burn out, or it will be unnecessarily costly.

Motion Control In a basic motion control system, Figure 6, the load represents the mechanics being positioned. The load is coupled or connected through one of the mechanical linkages described previously.

The motor may be a traditional PMDC servo motor, a vector motor, or a brushless servo motor. The control takes a low level incoming command signal and amplifies it to a higher power level for driving the motor.

The programmable motion controller is the brain of the motion system. The motion controller is programmed to accomplish a specific task for a given application. By comparing a preprogrammed, “desired” position with the feedback “actual” position, the motion controller can take action to minimize an error between the actual and desired load positions.

Figure 6 – Basic motion system

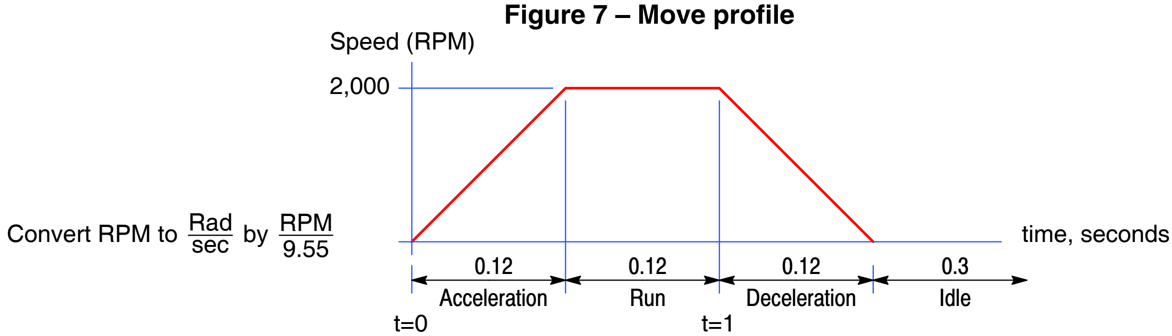


Nomenclature:

1REV= 2π radians (per revolution)
α_{acc} = Rotary acceleration, radians/sec^2
I_{acc} = Current during acceleration, Amps
I_{RMS} = Root–mean–squared current, Amps
J_L = Load inertia, lb–in–s^2
J_{ls} = Leadscrew inertia, lb–in–s^2
J_m = Motor inertia, lb–in–s^2
J_t = Total inertia (load plus motor), lb–in–s^2
K_t = Torque constant, lb–in/Amps
P = Total power, Watts
P_{del} = Power delivered to the load, Watts
P_{diss} = Power (heat) dissipated by the motor, Watts
R_m = Motor resistance, ohms
S_m = Motor speed, RPM
t_{acc} = Acceleration time, sec
t_{dec} = Deceleration time, sec
t_{idle} = Idle time, sec
t_{run} = Run time, sec
T = Torque, lb–in
T_{acc} = Acceleration torque, lb–in
T_{dec} = Deceleration torque, lb–in
T_f = Friction torque, lb–in
T_{RMS} = Root–mean–squared torque, lb–in
T_{run} = Running torque, lb–in
T_s = Stall torque, lb–in

Move Profile A move profile defines the desired acceleration rate, run time, speed, and deceleration rate of the load. For example, suppose with a system at rest (time=0, Figure 7), the motion controller issues a command to the motor (through the control) to start motion. At t=0, with full power supply voltage and current applied, the motor has not yet started to move. At this instant, there is no feedback signal, but the error signal is large.

Figure 7 – Move profile



As friction and torque are overcome, the motor and load begin to accelerate. As the motor approaches the commanded speed, the error signal is reduced and, in turn, voltage applied to the motor is reduced. As the system stabilizes at running speed, only nominal power (voltage and current) are required to overcome friction. At t=1, the load approaches the desired position and begins to decelerate.

In applications with similar move profiles, most of the input energy is dissipated as heat. Therefore, in such systems, the motor's power dissipation capacity is the limiting factor. Thus, basic motor dynamics and power requirements must be determined to ensure adequate power capability for each motor.

Determining acceleration rate is the first step. For example, with a movement profile as shown in Figure 7, the acceleration rate can be determined from the speed and acceleration time. (Dividing the motor speed expressed in RPM by 9.55 converts the speed to radians per second.)

$$\frac{\text{Speed}}{\text{Accel Time}} = \text{Acceleration Rate} = \alpha_{acc} = \frac{S_m}{9.55\ t_{acc}} = \frac{2000}{9.55 \times 0.12} = 1745.2\ \text{rad./s}^2$$

Acceleration Torque

The torque required to accelerate the load and overcome mechanical friction is:

$$T_{acc} = J_t(\alpha_{acc}) + T_f$$

Example: An application requires moving a load with a leadscrew.
The load parameters are:
Weight of load (W_{lb}) = 200 lb, leadscrew inertia (J_{ls}) = 0.00313 lb–in–s^2, friction torque (T_f) = 0.95 lb–in acceleration rate (α_{acc}) =1745.2 rad./ s^2.
Motor parameters are:
Motor inertia (J_m) = 0.0037 lb–in^2, continuous stall torque (T_s) = 14 lb–in, torque constant (K_t) = 4.8 lb–in/A and motor resistance (R_m) = 4.5 ohms.
Acceleration torque can be determined by:

$$T_{acc} = (J_L + J_{ls} + J_m)(\alpha_{acc}) + T_f$$

$$T_{acc} = (.00052 + .00313 + .0037)1745.2 + 0.95 = 13.77\ \text{lb–in.}$$

Duty Cycle Torque In addition to acceleration torque, the motor must be able to provide sufficient torque over the entire duty cycle or move profile. This includes a certain amount of constant torque during the run phase, and a deceleration torque during the stopping phase. Running torque is equal to friction torque (T_f), in this case, 0.95 lb–in. During the stopping phase, deceleration torque is:

$$T_{dec} = -J_t(\alpha_{dec}) + T_f = -(.00052 + .00313 + .0037)\,1745.2 + 0.95 = -11.87 \text{ lb–in}$$

Now, the root–mean–squared (RMS) value of torque required over the move profile can be calculated:

$$T_{RMS} = \sqrt{\frac{T_{acc}^{\,2}(t_{acc}) + T_{run}^{\,2}(t_{run}) + T_{dec}^{\,2}(t_{dec})}{t_{acc} + t_{run} + t_{dec} + t_{idle}}}$$

Note: Accel, run, etc. times are provided in Figure 7.

$$T_{RMS} = \sqrt{\frac{(13.77)^2(.12) + (.95)^2(.12) + (11.87)^2(.12)}{.12 + .12 + .12 + .3}} = 7.75 \text{ lb–in}$$

The motor selected for this application can supply a continuous stall torque of 14 lb–in, which is adequate for the application.

Control Requirements

Determining a suitable control (amplifier) is the next step. The control must be able to supply sufficient accelerating current (I_{acc}), as well as continuous current (I_{RMS}) for the application's duty cycle requirements. Required acceleration current that must be supplied to the motor is:

$$I_{acc} = \frac{T_{acc}}{K_t} = \frac{13.77}{4.8} = 2.86 \text{ Amps}$$

Current over the duty cycle, which the control must be able to supply to the motor, is:

$$I_{RMS} = \frac{T_{RMS}}{K_t} = \frac{7.75}{4.8} = 1.61 \text{Amps}$$

Thus the servo control selected must supply currents of 2.86 amps for acceleration and 1.16 amps continuously (RMS over the duty cycle).

Power Requirements

The control must supply sufficient power for both the acceleration portion of the movement profile, as well as for the overall duty cycle requirements. The two aspects of power requirements include:

- Power delivered to move the load, P_{del} and
- Power losses dissipated in the motor, P_{diss}.

Power during acceleration time is:

$$P_{del} = \frac{\text{torque x speed}}{63,025} \text{ x } 746 = \frac{T\,(S_m)}{63,025} \text{ x } 746 = \frac{13.75 \text{ x } 2000}{63,025} \text{ x } 746 = 325.5 \text{ Watts}$$

Power dissipated in the motor is:

$$P_{diss} = I^2\,PK\,(R_m) = (2.86)^2\,(4.5)\,(1.5) = 55 \text{ Watts}$$

Note: The factor of 1.5 in the P_{diss} calculation is a factor used to make the motor's winding resistance "hot." This is a worst case analysis, assuming the winding is at 155 °C.

The sum of these "P_{del}" and "P_{diss}" determine total power requirements.

$$P = P_{del} + P_{diss} = 325 + 55 = 380 \text{Watts}$$

Power Requirements Continued

Continuous power required for the duty cycle is:

$$P_{del} = \frac{T_{RMS}\,S_M}{63,025} X\,(746) = \frac{7.75(2,000)}{63,025}\,(746) = 183 \text{ Watts}$$

$$P_{diss} = I_{RMS}\,(R_M) = (1.61)^2(4.5)(1.5) = 17 \text{ Watts}$$

$$\emptyset \quad P = P_{del} + P_{diss} = 183 + 17 = 200 \text{ Watts}$$

The control selected must be capable of delivering (as a minimum) an acceleration (or peak) current of 2.86 Amps, and a continuous (or RMS) current of 1.61 Amps. The power requirement calls for peak power of 380 W and continuous power of 200 Watts.

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