TYPICAL APPLICATIONS

TYPICAL APPLICATIONS			
Market Segment & Application	**Approx HP Range**	**Description**	**Requirements**
CONVERTING AND PRINTING			
Sheeter	5-20	A machine used to feed a continuous web of paper into a cutter, cutting it to length.	• Inverse ratio -- calibrated to sheet length, ± 1/64" • Master/slave control • Regen operation
MATERIAL HANDLING			
Lowerator	20-125	Used to handle logs or rolls of paper. Moves them from a higher to lower level.	• Very good torque and speed control • Handles high peak and rms loads • Precise stopping requires precise accel/decel rates • High torque/inertia ratio motors
Shuttle Car	10-30	Large, heavy car that runs on tracks, capable of carrying 40,000 pounds or more. Has traverse conveyors for moving product.	• Capable of handling line voids • 4-quadrant regen • Handles high peak and rms loads • Rugged motor construction
PLASTICS			
Extruder	40-300	Feed auger that also accomplishes shear heating and mixing of thermo-plastic material. Horsepower requirement roughly correlates to feed screw diameter. Most common plastics application.	• High efficiency • Low maintenance • Good low speed torque
Co-Extrusion	5-150	A series of extruders putting material at very exact proportions into the same die.	• Good speed (ratio) stability • Good ratio and following control
Crammer/ Feeder	5-30	A device used to "cram" material into the extruder throat, rather than use a gravity feed.	• TENV enclosure required because of the dusty environment • Good low speed torque • Needs torque control (torque limited, speed controlled), e.g. PVC manufacturing
Pullers	2-15	A set of friction rollers used to pull material out of an extruder die at a precise rate, to assure constant cross-sectional dimension. The wall thickness can be controlled or changed by pulling at precise rates.	• TENV enclosure • Accurate ratio control
Film Lines	.5-5	Extruder with a film die, either circular (blown film) or flat (cast film) and appropriate downstream equipment.	• TENV enclosure • Accurate ratio control
Blow Molding	20-250	Blow molding takes an extruded hollow piece of plastic material, called a parison, then closes a mold around it and injects air into it to "blow" the material into the shape of the mold. Used to produce hollow shapes.	• High torque • Continuous operation • High efficiency
Injection Molding	2-100	Injection molding injects the plastic material directly into a mold under high pressure, without "blowing" it. Used to produce solid shapes.	• The extruder on an injection molding press is typically hydraulic, due to the pressures used, but other drives need to have the position control and fast response and cycle times of a servo-type system.

Other Market Segments and Applications to consider:

Material Handling
- Belt feeders
- Reciprocating feeders

Paper
- Planers
- Dryers
- Converting machines
- Beaters/Pulpers
- Slab conveyors
- Choppers

Machine Tool
- Bending rolls
- Punch presses
- Tapping machinery

Metal Forming/Rolling
- Draw bench carriages
- Slitters
- Extruders
- Reel drives
- Rod drives
- Edger drives

Rubber Industry
- Extruders
- Tire-building machines
- Mixing mills

TYPICAL APPLICATIONS (CON'T)

TYPICAL APPLICATIONS (CON'T)			
Market Segment & Application	**Approx HP Range**	**Description**	**Requirements**
TEST STANDS			
Drive Shafts	30-200	Prime mover motor and load motor for applying forward or reverse speed and torque on drive shafts and CV joints.	• High speed • High horsepower • Broad, constant power range
Hydraulic Pumps	5-400	A prime mover motor to turn the pump under test and a load motor to load a hydraulic motor under load.	• High efficiency • Good bandwidth (fast response) • Ability to handle very sharply applied loads • Common bus is a huge advantage • Wide range of torque and speed
Jet Fuel Pump	5-50	Prime mover motor for hydraulic pump that simulates a jet engine.	• Class I, Div. 2 or Div. 1 hazardous location ratings • High speed • High accuracy over broad range of rapidly changing loads
Twin Outdrive	50-150	Prime mover motor and two load motors to simulate a driving engine and two counter-rotating propellers.	• Common bus for efficiency • Efficient power regeneration • Good speed and torque control in all directions
TEXTILES			
Ride-Through Generator	40+	This is a regen drive connected via a common bus to other Pacific Scientific drives. It uses flywheel energy to keep production lines running through short power interruptions.	• Efficient no-load operation • Line-loss sensing scheme • Controlled DC bus
Spinning	.5-10	Drawing (spinning) a thread to orient the material and thereby increase the strength. Usually associated with man-made thread, which is extruded through a multi-hole die.	• Very precise ratio control • Synchronous operation of multiple drives
Warper/ Beamer	30-125	A winder that winds parallel threads onto a cylindrical drum (beam) for use later in a weaving loom.	• TENV or TEAO enclosures required because of lint • Very good bandwidth (response time) • Torque control if no dancer is used • Quick stopping
Draw Warping	30-125	A single machine doing both drawing (spinning) and warping in one operation.	• Needs a sophisticated drive system, with extremely good control -- down to zero speed • High bandwidth • Good power ride-through • Needs frequency reference and feedback
WIRE/CABLE			
Accumulator	1-10	A place to keep the product while a downstream process is stopped, so the need to stop all processes is prevented.	• Full 4-quadrant operation • Ability to be pulled backward or forward from zero speed • Good torque and speed control
Take-Up (Torque)	.5-3	This is a winder with a levelwind or traversing mechanism. It is usually mechanical. Most take-ups are simple tension/torque devices	• Economical • Rugged construction • Torque or dancer control
Twister/ Cabler	Up to 30	Combines a number of small gauge wires into a group (cable).	• Precise ratio control • Synchronous following at 1:1

MOTOR PERFORMANCE CURVES

The specification section of this selection guide shows the motor ratings, characteristics, torque/speed curves, power/speed curves, and efficiency profiles for standard motors. Performance characteristics can be customized for specific applications.

TORQUE/SPEED CURVES

Figure 1 shows a typical torque/speed curve, along with its rated torque, speed, and current parameters, from the "Performance Curves" section of this selection guide. The curves represent typical motor performance when driven by a brushless motor drive with a 640V dc bus, a sinusoidal current output, and continuous and peak current capabilities to match the motor ratings in the table. Note that the curve shows both continuous and intermittent duty areas of operation.

Figure 1: E184E1 DPBV performance curve and table

E184E1 MOTOR

Reference Points	
T_{PK}	310
T_{CS}	86
T_{CR}	79
W_R	1,750
I_{CS}	49.0
I_{CR}	31.5

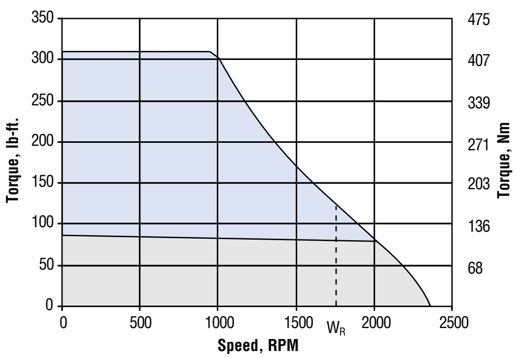


Figure 1

Intermittent duty

Continuous duty

CONTINUOUS DUTY AREA

The motor may be operated at any speed and torque within the continuous duty area for any length of time. The area is bordered by the continuous torque output line and the maximum speed line.

The continuous torque line represents the maximum torque the motor can produce continuously at different speeds without exceeding the rated winding temperature of 140°C in a 40°C ambient (See "Ambient Temperature Derating", page 70). It is a function of the motor's cooling.

The maximum speed line represents the maximum speed the motor can reach at different loads. It is a function of the bus voltage of the drive (640V dc for these curves) and the motor winding. Different windings may produce higher maximum speeds, but at the expense of higher current required to produce a given torque.

INTERMITTENT DUTY AREA

The motor may be operated at any speed and torque within the intermittent duty area for shorter lengths of time. The area is bordered by the peak torque output line and the maximum speed line.

The peak torque line represents the maximum torque produced by the motor at rated temperature when the drive is applying the maximum instantaneous current the motor can withstand. For the PACTORQ Series curves, it is a function of the demagnetization current at maximum rated temperature.

A motor may normally operate safely in an application which requires operation in the intermittent duty area if the calculated RMS (Root Mean Square) torque falls within the continuous duty area. (See page 79, "Determining Continuous (RMS) Torque")

Some of the torque/speed curves do not indicate continuous operation to the maximum speed capability of the winding. In those cases, the rotational losses of the motor will not allow continuous operation above a limiting speed. However, short time operation above the continuous speed limit is permitted. Such a winding can be used in situations where intermittent operation at high speeds is desirable. Examples are applications requiring rapid traverse to position and fast return to home.

POWER CURVES

Figure 2, the power curve for the E184 DPBV motor, shows continuous motor output power capability plotted versus speed. It illustrates PACTORQ's capability of producing extremely high horsepower at high speeds. In this case, the motor is rated at 27 Hp at 1750 RPM, but is capable of producing over 60 Hp at 6000 RPM! A special winding is required for greater than 3600 RPM operation, and a special rotor is required for greater than 6000 RPM operation.

Figure 2: E184 DPBV Power Curve

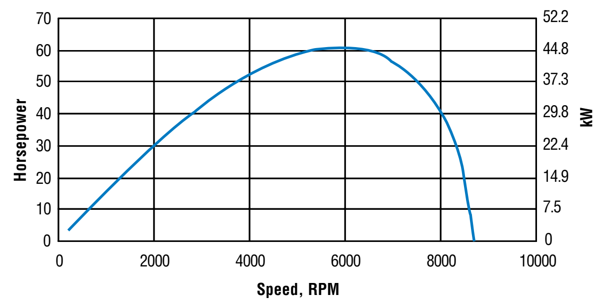


Figure 2

EFFICIENCY CURVES

Figure 3, the efficiency curve for the E184 motor, shows motor efficiency contours plotted versus speed and torque. It illustrates PACTORQ's capability of operating with very high efficiency over a broad speed and load range. In this case, the motor efficiency is 94% at 3600 RPM and 120 lb-ft, at 1250 RPM and 25 lb-ft, and at 3500 RPM and 20 lb-ft!

Figure 3: E184 Efficiency Curve

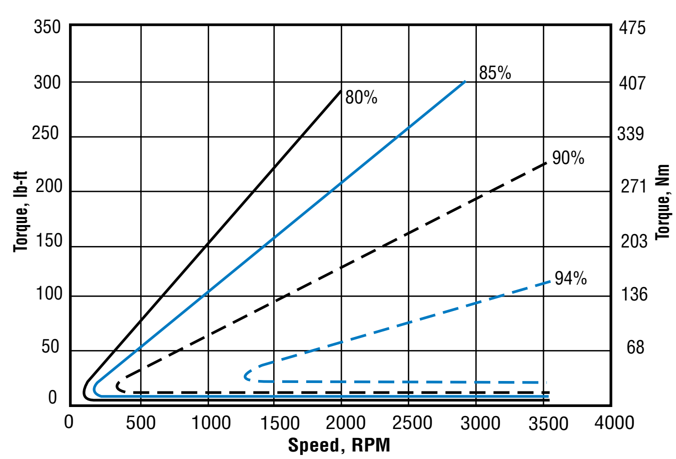


Figure 3

DEFINING LOAD PARAMETERS AND MOTION PROFILES

This section covers the building blocks for sizing and selecting a brushless motor. Terminology covering torque, inertia, and motion profiles will be explained and calculations will be used to determine running speeds and acceleration rates. Included are the most common types of speed profiles for constant speed and incremental motion applications.

LOAD PARAMETERS

There are five basic load parameters which have to be determined as the first step in selecting a brushless motor. These parameters are defined at the motor shaft, so the effect of mechanical linkages (gears, reducers, belts & pulleys, etc.) between the motor and the load must be taken into account.

FRICTION TORQUE T_F (lb-ft)

Torque is required to overcome the contact friction before one mechanical surface will move across another. It can be calculated, but is more easily measured. Whenever possible, it should be measured by attaching a torque wrench at the driving shaft.

VISCOUS TORQUE T_V (lb-ft/kRPM)

This is the torque required to “shear” a viscous material (usually oil or grease) between two surfaces. Windage is included in this component of torque, even though it is caused mainly by parts on the machine moving through air.

In some applications viscous torque can be quite high. It is usually higher at higher speeds. For the majority of applications, however, this torque is negligible.

ACCELERATION TORQUE T_J (lb-ft)

This is the torque required to accelerate or decelerate an inertial load to a new speed (which may be zero speed) in a given amount of time.

Loads with a large mass (high inertia) require acceleration torque which is high compared to the running or friction torque.

LOAD TORQUE T_L (lb-ft)

This is any torque required by the load other than those described above.

A common example of this type of torque is an external force applied to the load, such as the force of gravity on an object being held in the air.

INERTIA J (lb-ft-sec^2)

Inertia is a measure of the resistance of an object to a change in velocity, that is, the resistance to accelerate or decelerate. Inertia can be calculated or measured, but is often the most difficult parameter to define. See the section on page 79 for methods of calculation for common inertial loads.

MOTION PROFILE PARAMETERS

You need to define a speed versus time profile to characterize the requirements of the motor you are trying to size. This profile, along with the load parameters, is used to determine the torques and speeds required of the motor. Again, the definition of these profiles is at the motor shaft, taking into account mechanical linkages. There are three basic profiles:

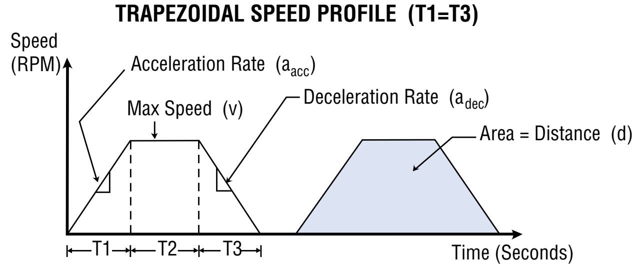
1. Trapezoidal – the most basic definition of what a motor does.
2. Triangular – a special case of the trapezoidal where running time is zero
3. Constant Speed – a special case of the trapezoidal where running time is longer.

Other profiles may be built from these basic profiles.

TRAPEZOIDAL SPEED PROFILE

The most basic speed profile is the trapezoidal (Figure 4). It involves accelerating a load from a speed (which is usually, but not always zero) to a new speed. The new speed is maintained for some period of time, after which the load is decelerated back to the original speed. This profile is very common in incremental motion and positioning applications.

TRAPEZOIDAL SPEED PROFILE (T1=T3)



Solving for Max Speed:
If T1 = T3 then

$$v = \frac{d}{T1 + T2}$$

Solving for Accel/Decel rates

$$a_{acc} = \frac{v}{T1} \text{ or } a_{dec} = \frac{v}{T3}$$

Where:
d = Motor move (revs)
v = Motor Speed (rev/sec)
T1 = Accel time (sec)
T2 = Max Speed time (sec.)
T3 = Decel time (sec.)
a = Accel/Decel rate (rev/sec^2)

Conversions:
RPM = 60 x rev/sec
Rad/sec = .1047 x RPM

Figure 4

You must specify the distance to be traveled or the speed to be reached AND the times T1, T2, and T3. Figure 4 shows the case where T1 (acceleration time) and T3 (deceleration time) are assumed to be equal (a simplification which reflects a very common circumstance).

Example: There is a load that must move 20 inches in 5 seconds. We find that the motor is required to move 100 revolutions to accomplish this. If we allow 1 second for acceleration and 1 second for deceleration, then the maximum speed required is 100 / (1+3) = 25 rev/sec. This will require an acceleration rate (and deceleration rate) of 25 rev/sec^2 and a top speed of 25 $\times$ 60 = 1500 RPM.

If you specify distance to be moved and speed to be reached (such as for a specific motor), you can calculate the **pre-decel** time required by the formula: **T = d / v** where T = T1 + T2.

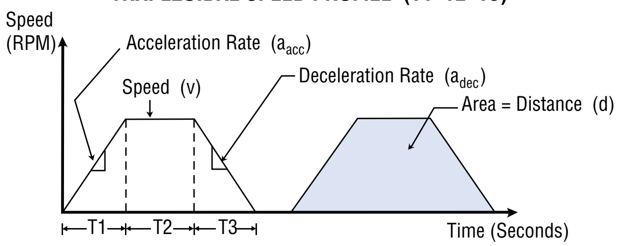
Example: In the previous example, we want to shorten the cycle time by going to 1800 RPM at the motor. If we still allow 1 second for acceleration, how long will the cycle time be?

1800 RPM / 60 = 30 rev / sec. The pre-decel time = 100 / 30 = 3.33 seconds.

If we allow 1 sec for acceleration, we must accelerate at 30 rev/sec^2, and the total time will be 3.33 sec plus 1 second for deceleration = 4.33 seconds.

A special case of the trapezoidal profile occurs when the acceleration time, the deceleration time, and the running time are all equal, as shown in Figure 5.

TRAPEZOIDAL SPEED PROFILE (T1=T2=T3)



Solving for Speed:

$v = \frac{(1.5 \times d)}{T1 + T2 + T3}$

Solving for Accel/Decel rates

$a_{acc} = \frac{v}{T1}$ or $a_{dec} = \frac{v}{T3}$

Where:
d = Motor move (revs)
v = Motor Speed (rev/sec)
T1 = Accel time (sec)
T2 = Max Speed time (sec.)
T3 = Decel time (sec.)
a = Accel/Decel rate (rev/sec^2)

Conversions:
RPM = 60 x rev/sec
Rad/sec = .1047 x RPM

Figure 5

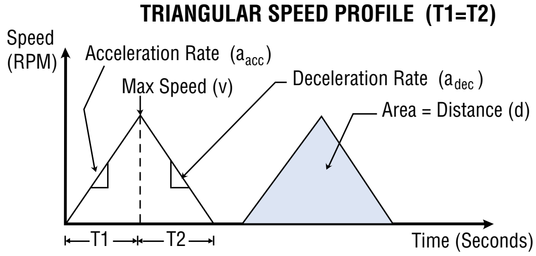
Setting all of the times equal simplifies calculations quite a bit. It is also easier on the motor than rapid acceleration to speed and rapid deceleration down. The down side is that it may not take full advantage of the speed of the motor and it may not work in all cases.

Example: With our previous load that must move 20 inches in 5 seconds, we had to move 100 revolutions in 5 seconds. If we re-calculate the example, setting all the profile times equal results in a maximum speed of (1.5 × 100) / 5 = 30 rev/sec (1800 RPM). In this particular case, though, our new acceleration rate is 30 / 1.6667 = 18 rev/sec^2, as opposed to 25 rev/sec^2 before. This may make it possible, depending on other factors, to use a smaller motor.

TRIANGULAR SPEED PROFILE

The triangular speed profile is a special case of the trapezoidal speed profile where the running time has been reduced to zero time. The triangular speed profile is illustrated in Figure 6.

TRIANGULAR SPEED PROFILE (T1=T2)



Solving for Max Speed:

$v = \frac{(2 \times d)}{T1 + T2}$

Solving for Accel/Decel rates

$a_{acc} = \frac{v}{T1}$ or $a_{dec} = \frac{v}{T2}$

Where:
d = Motor move (revs)
v = Motor Speed (rev/sec)
T1 = Accel time (sec)
T2 = Max Speed time (sec.)
a = Accel/Decel rate (rev/sec^2)

Conversions:
RPM = 60 x rev/sec
Rad/sec = .1047 x RPM

Figure 6

The triangular speed profile is the potentially the fastest movement profile, but it is also the hardest on the motor, switching directly from acceleration to deceleration, possibly in current limit.

Example: In the previously stated example, remember that the load must move 20 inches in 5 seconds, or 100 revolutions in 5 seconds at the motor. If we re-calculate the example on a triangular profile, setting the profile acceleration time equal to deceleration time, we find that the maximum speed is 2 × 100 / 5 = 40 rev/sec (2400 RPM). The acceleration time, though is 2.5 seconds, so the actual acceleration rate is only 40 / 2.5 = 16 rev/sec^2.

We can compare the three profiles we have looked at in table A:

	Trapezoidal T1=T3	Trapezoidal T1=T2=T3	Triangular T1=T2	Units
distance	100	100	100	revolutions
time	5	5	5	seconds
accel time	1	1.67	2.5	seconds
accel rate	25	18	16	rev/sec^2
run time	3	1.67	0	seconds
max speed	1500	1800	2400	RPM
decel time	1	1.67	2.5	seconds
decel rate	25	18	16	rev/sec^2

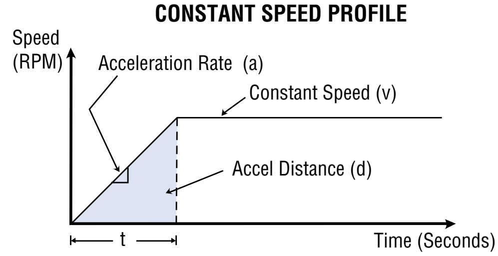
Table A

As you can see, there are trade-offs to be made between the types of profiles for a given load and its movement. The trapezoidal forms require higher accel and decel rates and greater peak torques and currents, but the triangular profile requires higher speeds and probably higher RMS torques.

CONSTANT SPEED PROFILE

The constant speed profile is a special case of the trapezoidal profile where the run time stretches out indefinitely. This is illustrated in Figure 7.

CONSTANT SPEED PROFILE



Solving for Constant Speed:
$v = a \times t$

Solving for Accel Rate

$a = \frac{v}{t}$

Solving for Accel Distance
$d = 1/2\ a \times t^2$

Where:
v = Motor Speed (rev/sec)
T = Accel time (sec)
a = Accel/Decel rate (rev/sec^2)
d = Distance (revs)

Conversions:
RPM = 60 x rev/sec
Rad/sec = .1047 x RPM

Figure 7

The calculations for the Constant Speed profile are very straightforward. You can find the accel rate to calculate torque by knowing the final speed and time of acceleration. In some applications, the acceleration distance may be of interest. RMS torque calculation should not be significant unless the peak torque during acceleration far exceeds the running torque.

CALCULATING PEAK AND RMS TORQUES AND INERTIAS

Using the speed profiles and the load parameters, it is possible to draw a torque versus time profile for a given application. This torque profile and the speed profile describes the torque/speed operating envelope required to drive the load.

Selection of a motor is accomplished by comparing the generated torque/speed profile to the torque/speed curves of likely motors. Once a motor is selected, a suitable drive must be selected which will operate the motor according to the required output.

CALCULATING PEAK TORQUE REQUIREMENTS

The torque required to drive the load is defined by the equation:

$$T = T_F + T_V + T_L + T_J \qquad (1)$$

Where:
T = required torque
T_F = friction torque
T_V = viscous torque
T_L = load torque
T_J = torque to accel/decel inertia

Friction and load torque have been previously defined. T_J, the torque to accelerate or decelerate the load inertia is defined by the formulas:

for accel: $T_{JA} = J \times a \qquad (2)$
for decel: $T_{JD} = -J \times d$

Where:
T_{JA} = acceleration torque
T_{JD} = deceleration torque
J = inertia
a = acceleration rate
$-d$ = deceleration rate

Note that deceleration rate is negative.

Viscous torque, T_V, is proportional to speed and can be defined by the formula:

$$T_V = K_{DV} \times v \qquad (3)$$

Where:
T_V = viscous torque
K_{DV} = damping constant
v = speed

Substituting equations (2) and (3) into (1) results in:

for accel: $T_{acc} = T_F + T_L + K_{DV} \times v + J \times a \qquad (4a)$
for decel: $T_{dec} = T_F + T_L + K_{DV} \times v - J \times d \qquad (4b)$

By inserting the maximum acceleration/deceleration rate and the maximum speed into equation (4), the peak torque requirements can be calculated:

for peak accel: $T_{acc} = T_F + T_L + K_{DV} \times v_{max} + J \times a_{max} \qquad (5a)$
for peak decel: $T_{dec} = T_F + T_L + K_{DV} \times v_{max} - J \times d_{max} \qquad (5b)$

Note that for these formulas the inertia is the total system inertia, i.e. motor inertia plus the total load inertia reflected to the motor shaft.

In many applications, T_L and T_V are considered negligible and can be ignored, hence reducing the formula to:

for peak accel: $T_{acc} = T_F + J \times a_{max} \qquad (6a)$
for peak decel: $T_{dec} = T_F - J \times d_{max} \qquad (6b)$

Inserting the known load and speed profile parameters into equations (5) or (6), the peak torque requirement can be calculated. The peak torque should be calculated for both acceleration and deceleration and then the larger of the two torque values used as the peak torque requirement for selecting the correct motor. In the case of the constant speed profile, acceleration will determine the peak torque value. The drive must supply a current value that equals or exceeds the peak current requirement.

The calculated peak torque must fall within the intermittent duty area on the motor's torque/speed curve. A safety margin is often added to the peak torque values to allow for increases in friction torque, viscous torque, load torque, and/or inertia. The size of the safety margin should consider the magnitude of the variation expected.

DETERMINING CONTINUOUS (RMS) TORQUE

The Brushless motor is sized and selected based on its continuous duty torque, or its RMS torque. The motor's continuous duty area curve defines the safe thermal limits at which the motor can operate. The accel, running, and decel torques, and their respective times as well as the dwell time between the moves, must be considered in its calculation. Figure 8 shows a typical trapezoidal speed profile and its associated torque profile. As stated previously, this profile is common in incremental motion applications. This figure assumes that the load torque and viscous torque are zero. It also assumes that the acceleration rate equals the deceleration rate.

During time ta, the load is accelerated from zero to speed v_{max}. The torque required to accomplish this acceleration is calculated from equation (6a).

Upon reaching v_{max}, the load is run at constant speed for time tr. Since there is no acceleration or deceleration during this interval, the only torque required is that necessary to overcome friction (load torque and viscous torque assumed zero).

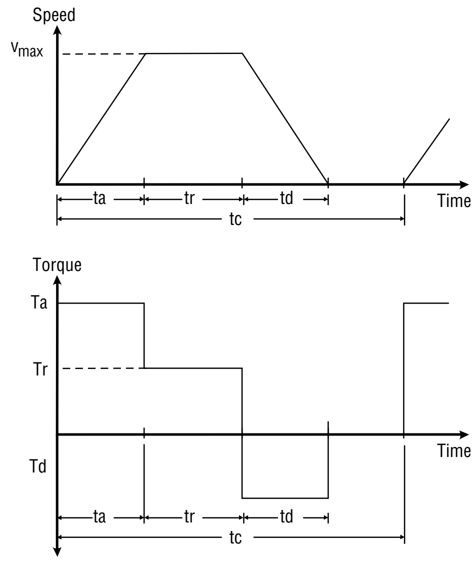


Figure 8

During time td, the load is decelerated from v_{max} to zero. The torque required to accomplish this deceleration is calculated from (6b). Note that the magnitude of the decelerating torque Td is smaller than that of the accelerating torque Ta. This is due to the fact that the friction torque, T_F, assists in decelerating the load.

The remainder of the cycle time is spent at zero speed and requires no torque.

The continuous torque requirements are defined by the RMS torque calculated from the profile seen in Figure 8. The following formula is used to calculate RMS torque:

$$T_{RMS} = \sqrt{\frac{(Ta)^2(ta) + (Tr)^2(tr) + (Td)^2(td)}{tc}} \qquad (7)$$

The calculated RMS torque must fall within the continuous duty area of the performance curve.

Figure 9 shows a typical constant speed profile along with its torque profile.

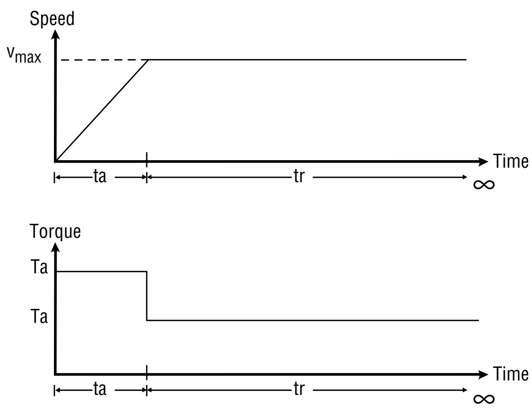


Figure 9

Again, during time ta, the load is accelerated from zero to speed v_{max}. The torque required to accomplish this acceleration is calculated from equation (6a).

However, upon reaching speed vmax, the load is run at constant speed for an infinite period of time. Only the torque required to overcome friction is necessary during this interval. Because the running time is much greater than the accel time, and there is, in theory, no deceleration (running time is infinite), the running torque becomes the motor's continuous duty torque, or RMS torque.

In the case of the constant speed profile, the three most important parameters for motor selection are the running torque, peak torque, and rated speed.

Regardless of the profile used, remember to derate the continuous duty area if the altitude exceeds 3300 feet or the motor ambient temperature is greater than 40°C. Also, remember to include safety margins in the calculations.

CALCULATING INERTIA

Inertia is the resistance of an object to a change in rotational velocity. In motion control applications, inertia is an important parameter since it defines the torque required to accelerate and decelerate the load. Figures 10a & b show two common cylinders and their related inertia formulas.

SOLID CYLINDER

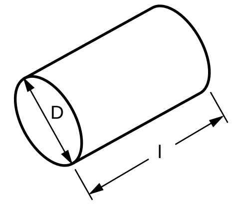


Figure 10a

For known weight and diameter

$$J_L = (\mathbf{.000875})\frac{W}{g}D^2 = (.000027)\,W\,D^2$$

For known density, diameter, and length

$$J_L = (\mathbf{.000681})\frac{lpD^4}{g} = (.000021)\,lpD^4$$

HOLLOW CYLINDER

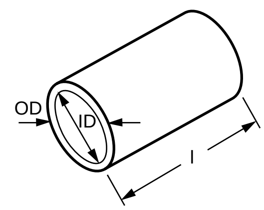


Figure 10b

For known weight and diameter

$$J_L = (\mathbf{.000875})\frac{W}{g}(OD^2 + ID^2) = (.000027)\,(OD^2 + ID^2)\,W$$

For known density, diameter, and length

$$J_L = (\mathbf{.000681})\frac{lp}{g}(OD^4 - ID^4) = (.000021)\,(OD^4 - ID^4)\,lp$$

Where:
- J_L = inertia (lb-ft-sec²)
- W = weight (lb)
- D = diameter (in.)
- OD = outside Diameter (in.)
- ID = inside diameter
- l = length (in.)
- p = density (lb/in³)
- g = gravitational constant (32.2 ft./sec²)

MATERIAL	DENSITY (lb/in³)
Aluminum	0.096
Brass	0.300
Bronze	0.295
Copper	0.322
Cold Rolled Steel	0.283
Plastic	0.040
Hard Wood	0.029
Soft Wood	0.018

Table B

MECHANICS OF MOTION

Most of the mechanical drive systems used with brushless motors can be divided into two basic categories: direct drive and gear drive. This section will examine sizing requirements for different load type applications and their calculations, provide a simple flowcharting method for step-by-step sizing considerations, and detail a rotary table sizing example.

LOAD TYPES

GEAR DRIVEN LOADS

In many industrial applications, the actual load speed is rotating at a different rate than the motor. The load parameters in a gear driven system have to be reflected back to the motor shaft by the gear ratio or the gear ratio squared. Figure 11 shows the components of the load, gearing, and motor.

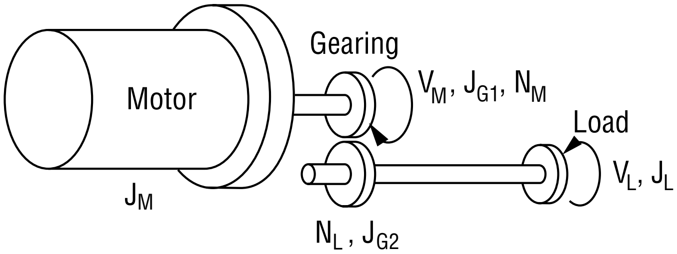


Figure 11

$$\text{Inertia}: J_T = \left(\frac{N_M}{N_L}\right)^2 (J_L + J_{G2}) + J_{G1} + J_M$$

$$\text{Speed}: V_M = V_L\left(\frac{N_L}{N_M}\right)$$

$$\text{Torque}: T_M = T_L\left(\frac{N_M}{N_L}\right)$$

Where:
V_M = motor speed (RPM)
V_L = load speed (RPM)
N_M = number of motor gear teeth
N_L = number of load gear teeth
T_M = load torque reflected to motor shaft (lb-ft.)
T_L = load torque not reflected through gearing (lb-ft.)
J_T = total system inertia reflected to shaft (lb-ft-sec^2)
J_L = load inertia (lb-ft-sec^2)
J_M = motor inertia (lb-ft-sec^2)
J_{G1} = motor gear inertia (lb-ft-sec^2)
J_{G2} = load gear inertia (lb-ft-sec^2)

DIRECT DRIVEN LOADS

In a direct driven load, the load parameters do not have to be reflected back to the motor shaft since no mechanical linkages are involved that would change the values. Figure 12 shows a simplified direct driven configuration with its parameters and related formulas.

Speed: $V_M = V_L$
Torque: $T_L = T_M$
Inertia: $J_T = J_L + J_M$

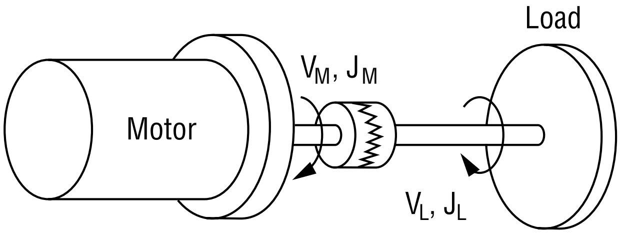


Figure 12

Where:
V_M = motor speed (RPM)
V_L = load speed (RPM)
J_T = total system inertia reflected to shaft (lb-ft-sec^2)
J_L = load inertia (lb-ft-sec^2)
J_M = motor inertia (lb-ft-sec^2)
T_M = load torque at motor shaft (lb-ft.)
T_L = load torque (lb-ft.)

Continued on next page.

TANGENTIALLY DRIVEN LOAD

In this type of load, the parameters have to be reflected back to the motor shaft. A tangential drive can be a conveyor, rack and pinion, timing belt and pulley arrangement, or chain and sprocket. It is important to include all pulley, sprocket, or pinion gear inertias in the calculations. Figure 13 shows the tangential drive and its respective formulas for speed, torque, and inertia.

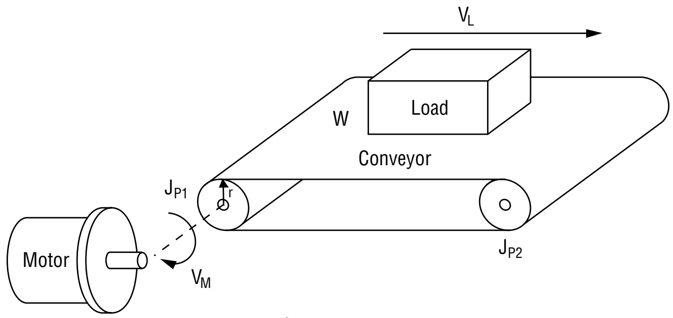


Figure 13

$$\text{Speed: } V_M = \left(\frac{1}{2\pi}\right)\left(\frac{V_L}{r}\right) = \left(\frac{(0.159)V_L}{r}\right)$$

$$\text{Torque: } T_L = F_L \times r$$

$$\text{Inertia: } J_T = \frac{1}{4}\left(\frac{W}{g}\right)D^2 = (0.0078)WD^2 + J_{P1} + J_{P2} + J_M$$

$$\text{Friction: } T_F = F_F \times r$$

Where:
- V_M = linear motor speed (RPM)
- V_L = load speed (RPM)
- r = pulley radius (feet)
- D = pulley diameter (feet)
- T_M = load torque reflected to motor shaft
- T_F = friction torque (lb-ft)
- F_L = load force (lb)
- J_T = total system inertia (lb-ft-sec^2)
- J_M = motor inertia (lb-ft-sec^2)
- J_{P1} &$_{P2}$ = pulley inertia(s) (lb-ft-sec^2)
- W = load weight including belt (lb)
- F_F = frictional force (lb)
- g = gravitational constant (32.2 ft/sec^2)

LEADSCREW DRIVEN LOAD

In leadscrew drive systems, the load parameters are reflected back through the leadscrew to the motor shaft. The inertia of the leadscrew has to be included and can easily be calculated using the inertia formula for solid cylinders. The leadscrew's efficiency and coefficient of friction must also be considered in the calculations. Typical efficiencies of various leadscrew types are shown in table C. Table D contains typical coefficients of friction. The leadscrew is sometimes preloaded to eliminate backlash in some positioning applications, and this preload torque must be added as it may be significant to the torque calculation. Figure 14 shows a leadscrew with its related formulas.

TYPE	EFFICIENCY
Ball Nut	0.9
Acme with Plastic Nut	0.65
Acme with Metal Nut	0.4

Table C

MATERIAL	µ
Steel on Steel	0.58
Steel on Steel (lubricated)	0.15
Teflon on Steel	0.04
Ball Bushing	0.003

Table D

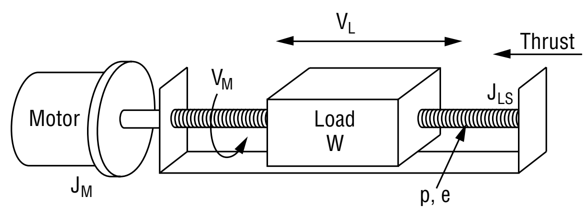


Figure 14

$$\text{Speed: } V_M = V_L \times p$$

$$\text{Torques: } T_{PL} = \left(\frac{F_{PL}}{2\pi p}\right) \times (0.2) = (0.0032)\frac{F_{PL}}{P}$$

$$T_F = \frac{F_F}{2\pi pe} = (0.159)\frac{F_F}{pe}$$

$$T_{TH} = \frac{F_{TH}}{2\pi pe} = (0.159)\frac{F_{TH}}{pe}$$

$$T_L = \frac{W}{2\pi pe} = (0.159)\frac{W}{pe}$$

$$T_T = T_{PL} + T_F + T_{TH} + T_L$$

$$\text{Friction: } F_F = \mu \times W$$

$$\text{Inertia: } JT = \frac{W}{g}\left(\frac{1}{2\pi p}\right)^2 \frac{1}{e} + J_{LS} + J_M = (7.88 \times 10^{-4})\frac{W}{p^2 e} + J_{LS} + J_M$$

Where:
- V_M = motor speed (RPM)
- V_L = linear load speed (ft/min.)
- p = lead screw pitch (revs/ft.)
- e = lead screw efficiency
- T_F = friction torque (lb-ft.)
- T_L = load torque (lb-ft.)
- T_{PL} = preload torque (lb-ft.)
- T_{TH} = thrust torque (lb-ft.)
- T_T = total torque (lb-ft.)
- F_F = friction force (lb.)
- F_{PL} = preload force (lb.)
- F_{TH} = thrust force (lb.)
- J_{LS} = leadscrew inertia (lb-ft-sec^2)
- J_M = motor inertia (lb-ft-sec^2)
- J_T = total system inertia (lb-ft-sec^2)
- W = load weight (lb.)
- µ = coefficient of friction
- g = gravitational constant (32.2ft/sec^2)

FLOWCHART SELECTION

The process of selecting a brushless motor is illustrated in chart 4.1. This flowchart presents a procedure for sizing a brushless motor in a simple, concise form which can be a handy reference tool. In some instances, selecting the correct motor will be an iterative process. Note, many of the motion and torque parameters shown are considered for incremental motion types of moves only. For constant speed sizing, use only those parameters and formulas that apply.

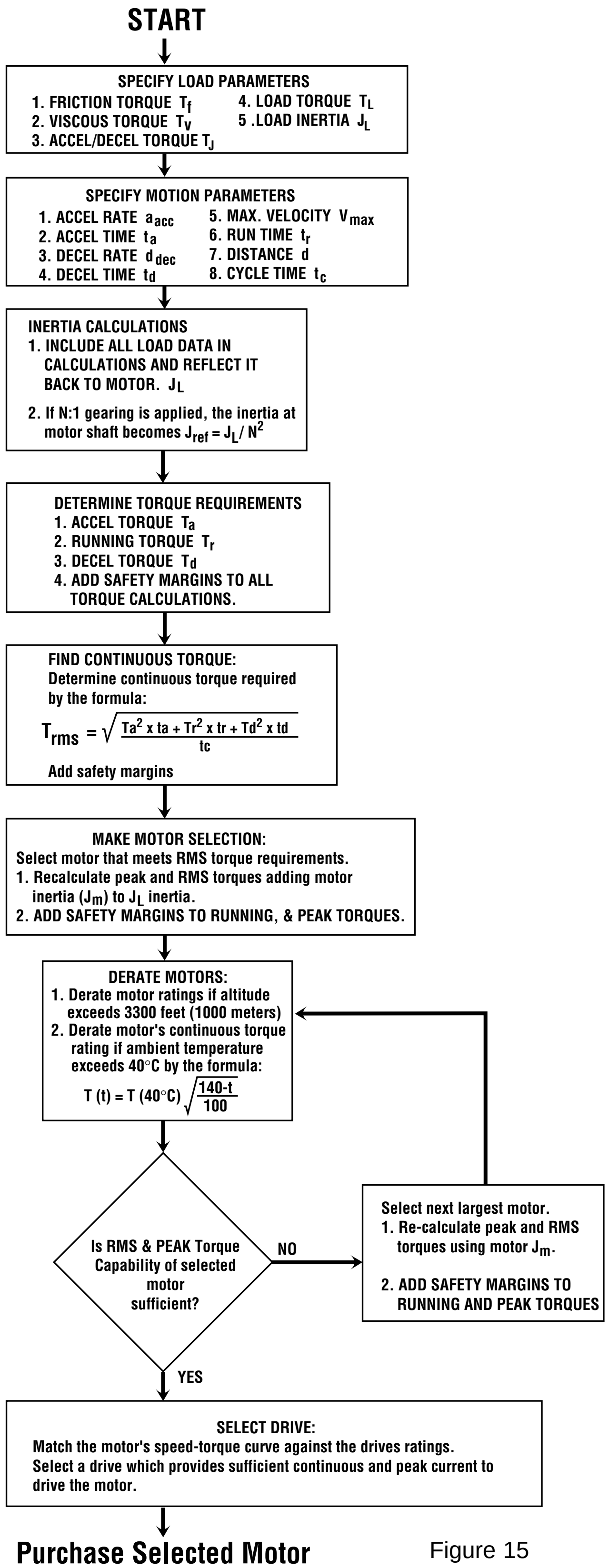


Figure 15

APPLICATION SIZING EXAMPLE

The following application example details a brushless motor sizing procedure. The application is for a rotary table which must be indexed through 4 positions per revolution. Each 90 degree index takes a total of 360 milliseconds with a 75 millisecond dwell between moves. The motor is in an ambient temperature of 40°C. The shaft is coupled through a 15:1 reducer with an 85% efficiency. Figure 16 shows the rotary table dimensions and the motor's speed profile for the required move time.

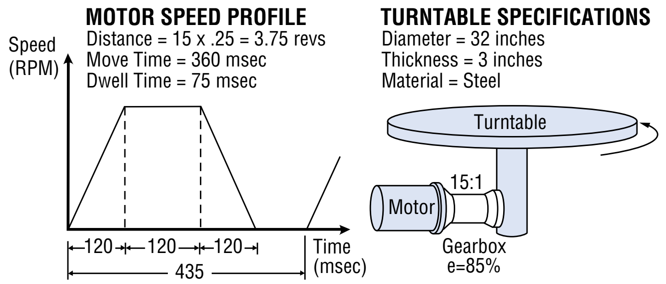


Figure 16

(VISCOUS, LOAD, AND FRICTION TORQUES T_V, T_L, T_F)

From the sizing flowchart shown, the first step is to define the 5 load parameters. The load is coupled through a 15:1 gearbox which is attached to a table shaft riding on lubricated steel ball bearings. We will assume that the viscous torque is zero. There are no externally applied torques so the load torque is zero. A friction torque of 15 lb-ft. is measured using a torque wrench attached to the table's drive shaft. To reflect this torque back to the motor through the gearbox, we use the following formula:

$$T_M = T_L\left(\frac{N_M}{N_L}\right)\left(\frac{1}{e}\right) = 15\text{ lb-ft.}\left(\frac{1}{15}\right)\left(\frac{1}{.85}\right) = 1.18\text{ lb-ft.}$$

Since the acceleration and deceleration torques are dependent on the accel and decel rates, the speed profile must be calculated before performing these calculations.

(LOAD INERTIA, J_L)

The rotary table is a solid cylinder of steel with a 32 in. diameter and a thickness of 3 inches. The inertia can be calculated if the weight or density of steel is known. By looking density up from table B for steel we find it to be 0.283 lb/in^3. The inertia formula for a solid cylinder is:

J_L = (0.000021) lpD^4 = (0.000021)(3.0")(0.283 lb/in^3)(32.0")^4
J_L = 18.9 lb-ft-sec^2

The inertia value shown is for the rotary table only. Objects placed on the table will add to the inertia. For this example, we will assume that the additional table weight of the objects placed on it is negligible and can be ignored.

(REFLECTED INERTIA, J_{REF})

The gearbox between the motor and rotary table will reflect the inertia seen at the motor by the gearbox ratio squared. The formula for reflecting the inertia is:

$$J_{REF} = J_L\left(\frac{N_M}{N_L}\right)^2 = \left(18.9\text{ lb-ft-sec}^2\right)\left(\frac{1}{15}\right)^2 = 0.084\text{ lb-ft-sec}^2$$

(ACCELERATION, DECELERATION, RUNNING SPEED, a_{ACC}, a_{DEC}, V)

The next step is to define the speed profile in terms of its acceleration rate, deceleration rate, and running speed. Figure 16 shows a trapezoidal profile where the accel time, running speed time, and decel time are equal. Referring to figure 6, the formula for calculating the running speed is:

$$v = \frac{1.5 \times d}{T1 + T2 + T3} = \frac{1.5 \times 3.75 \text{ revs}}{(120 + 120 + 120)\text{m sec}} = 15.625 \text{ revs/sec} = 938\text{rpm}$$

and

$$v = 938 \text{ rpm or } 98.2 \text{ rad/sec}$$

Since the acceleration and deceleration times are equal, we only need to calculate for the acceleration rate:

$$a_{acc} = \frac{v}{t_a} = \frac{98.2 \text{ rad/sec}}{.120 \text{ sec}} = 818 \text{ rad/sec}^2$$

therefore

$$a_{acc} = a_{dec} = 818 \text{ rad/sec}^2$$

Summarizing the reflected motion, torque, and inertia parameters through the gearbox yields:

Friction Torque:	T_F	= 1.18 lb-ft
Viscous Torque:	T_V	= 0 lb-ft
Load Torque:	T_L	= 0 lb-ft
Inertia (load):	J_{REF}	= 0.084 lb-ft-sec^2
Accel Rate:	a_{acc}	= 818 rad/sec^2
Accel Time:	t_a	= .120 sec
Decel Rate:	a_{dec}	= 818 rad/sec^2
Decel Time:	t_d	= .120 sec
Running Speed:	v	= 98.2 rad/sec = 938 rpm
Running Time:	t_r	= .120 sec
Distance:	d	= 3.75 rev
Cycle Time:	tc	= .435 sec

(ACCEL & DECEL TORQUES, T_{ACC}, T_{DEC})

Using the reflected parameter values from above and equations 5a and 5b from page 79, the peak torque requirements can be calculated. Note, however, that the inertia specified is reflected load inertia only and does not include the motor inertia. For consistency in units, inertia should remain in lb-ft-sec^2, and acceleration/deceleration should be in rad/sec^2.

for accel: T_{acc} = 1.18 + 0 + 0 + (0.084)(818) = 69.9 lb-ft
for decel: T_{dec} = 1.18 + 0 + 0 - (0.084)(818) = -67.5 lb-ft

A good rule-of-thumb is to add 20% safety margin to these calculations:

for accel: T_{acc} = (69.9 lb-ft)(1.2) = 83.9 lb-ft
for decel: T_{dec} = (-67.5 lb-ft)(1.2) = -81.0 lb-ft

From this it can be seen that the torque to accelerate the load is larger than that to decelerate the load.

(RMS TORQUE, T_{RMS})

The continuous torque must now be assessed. Using the RMS calculation in equation (7) on page 80, the following RMS torque is derived:

$$T_{RMS} = \sqrt{\frac{(T_{acc})^2(ta) + (T_r)^2(tr) + (T_{dec})^2(td)}{tc}}$$

$$T_{RMS} = \sqrt{\frac{(83.9)^2(.120) + (1.18)^2(.120) + (-81.0)^2(.120)}{0.120 + 0.120 + 0.120 + 0.075}}$$

$$T_{RMS} = 61.3$$

Since motor inertia has not yet been accounted for, we will add a 20% safety margin to the RMS torque, yielding:

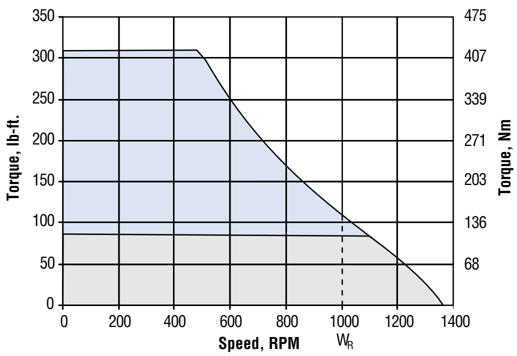
T_{RMS} = (613.3 lb-ft)(1.2) = 73.6 lb-ft

(ADDING MOTOR INERTIA, J_M)

Figure 17 shows the E184E3J DPBV motor's torque/speed curve. It has a continuous stall torque of 86 lb-ft. and a peak stall torque of 310 lb-ft. with rated peak torque at 938 rpm of 127 lb-ft. The continuous rated torque at 938 rpm is approximately 83 lb-ft. Hence the motor's continuous and peak torques are sufficient to meet the preliminary application requirements. The motor's inertia must now be added to the reflected load inertia and the peak torque and RMS torque will be recalculated.

E184E3 MOTOR

Reference Points	
T_{PK}	310
T_{CS}	86
T_{CR}	83
W_R	1,000
I_{CS}	19.0
I_{CR}	18.9



Intermittent duty

Continuous duty

Figure 17

for accel: T_{acc} = 1.18 + 0 + 0 + (0.084 + 0.0142)(818) = 81.5 lb-ft.
for decel: T_{dec} = 1.18 + 0 + 0 - (0.084 + 0.0142)(818) = -79.1 lb-ft.

adding 20% safety margin to these calculations:

for accel: T_{acc} = (81.5 lb-ft)(1.2) = 97.8 lb-ft
for decel: T_{dec} = (-79.1 lb-ft)(1.2) = -94.9 lb-ft

The RMS torque calculation is:

$$T_{RMS} = \sqrt{\frac{(97.8)^2(.120) + (1.18)^2(.120) + (-94.9)^2(.120)}{0.120 + 0.120 + 0.120 + 0.075}}$$

$$T_{RMS} = 71.6 \text{ lb-ft.}$$

Note, it is not necessary to add a safety margin to the RMS torque once the motor has been selected. The safety margin applied to the peak torque will be reflected in the RMS calculation. The E184E3J DPBV motor will provide more than adequate continuous and peak torque for this application.

Load parameters and speed profile parameters must be specified to allow proper sizing of a brushless motor. Using these parameters, peak torque, continuous torque, and maximum speed requirements can be calculated. These requirements are compared to the available motor performance curves and appropriate selection(s) can be determined. This example was used to point out the steps involved in sizing and selecting a motor for a specific load type. If you have additional questions you'd like to discuss about your specific application, contact application engineering.