Motor Selection and Sizing

Motor Selection

With each application, the drive system requirements greatly vary. In order to accommodate this variety of needs, Aerotech offers five types of motors.

Linear Motors

Advantages

- Highest acceleration, highest speed
- No backlash, windup or wear
- Brushless – no maintenance

Slotless Motors

Advantages

- Ultra-smooth operation
- Zero cogging
- Brushless – no maintenance

Disadvantages

- Complex amplifier design

Brushless Motors

Advantages

- High acceleration
- High torque
- Brushless – no maintenance

Disadvantages

- More complex amplifier design

DC Servomotors

Advantages

- Smooth operation, low-velocity ripple
- High torque

Disadvantages

- Brushes limit ability to continuously start and stop
- Brushes require maintenance

Microstepping Motors

Advantages

- Simple operation
- High torque at low speeds

Disadvantages

- Open loop
- Low acceleration capability
- More heat generation than servomotors

Motor Sizing Process

The following sections describe how to choose a motor using speed, torque, and inertia selection criteria. The basic procedure for sizing a motor is:

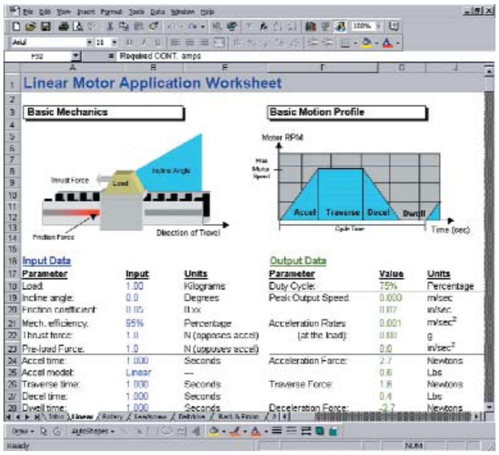
1. Determine move parameters
2. Calculate load inertia (or mass)
3. Calculate peak and rms torque (or force) requirements

While the steps for motor sizing remain constant, different mechanical systems require different formulas to calculate the first three steps. The selection of the motor is determined by the general characteristics of the motor desired and the ability of the motor to meet the calculated requirements.

Motor Sizing Software

Aerotech produces a Motor Sizing Workbook that is available on Aerotech's web site. This file can be downloaded HERE. The free-of-charge motor sizing sheet features the following application support:

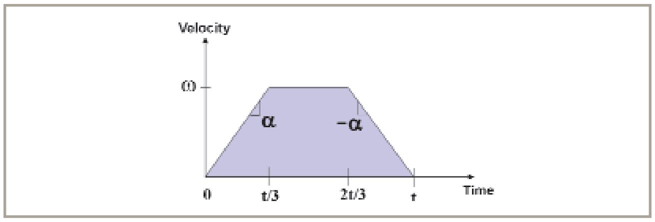
- Linear Motor
- Direct Drive
- Leadscrew
- Beltdrive
- Rack and Pinion



Motor Selection and Sizing CONTINUED

Motion Velocity Profile

The most common and efficient velocity profile for point-to-point moves is the “1/3-1/3-1/3” trapezoid. This profile breaks the time of the acceleration, traverse, and deceleration into three equal segments. The end result is that the profile provides the optimal move by minimizing the power required to complete the move.



If you know the move distance and time, you can quickly calculate the acceleration and velocity as follows:

Rotary

$$\alpha = \frac{4.5\,\theta}{t^2}$$

$$\omega_{avg} = \frac{\Delta\theta}{\Delta t}$$

$$\omega = 1.5\frac{\Delta\theta}{\Delta t}$$

where:

- α = acceleration in rad/s²
- θ = distance in radians
- t = total move time in seconds
- ω = peak velocity in rad/s

Linear

$$a = \frac{4.5\,x}{t^2}$$

$$v_{avg} = \frac{\Delta x}{\Delta t}$$

$$v = 1.5\frac{\Delta x}{\Delta t}$$

- a = acceleration in m/s²
- x = distance in meters
- t = total move time in seconds
- v = peak velocity in m/s

Inertia and Mass

In a rotary motor system, the best load-to-motor inertia match is 1:1 because it minimizes power consumption and increases system stability. Typically, systems will not achieve a 1:1 ratio; ratios as high as 10:1 can exist without adversely affecting system stability. For low bandwidth systems, higher ratios are acceptable but should be avoided due to the effect of decreased system stability.

In a linear motor system, the mass is direct-coupled to the moving coil (forcer). System stability is directly dependent on the stiffness of the mechanics and bandwidth of the servo controller.

Rotary

$$J = J_{motor} + J_{system}$$

Linear

$$m = m_{Forcer} + m_{Load}$$

Note: The inertia of a rotary system (J_{system}) is dependent on the mechanics of the system. The load in a linear motor system (m_{Load}) is the sum of all weights (kg used as a force) directly connected to the moving forcer coil.

Peak Torque and Peak Force

The total torque that a motor must produce to move itself and the load is:

Rotary

$$T_t = T_\alpha + T_f + T_\omega + T$$

where:

- T_t = total peak torque in N-m
- T_a = acceleration torque in N-m
- T_f = friction torque in N-m
- T_w = viscous torque in N-m
- T_g = gravity torque in N-m

Linear

$$F_t = F_a + F_f + F_g$$

- F_t = total peak force in N
- F_a = acceleration force N
- F_f = friction force in N
- F_g = gravity force in N

A simplified expression for acceleration torque and force that provides a reasonable estimation value is:

Rotary

$$T_\alpha = \frac{J_t\alpha}{e}$$

where:

- T_α = acceleration torque
- J_t = total inertia in kg-m²
- α = acceleration in rad/s²
- e = transmission efficiency

Linear

$$F_a = \frac{m_t a}{e}$$

- F_a = acceleration force
- m_t = total mass in kg
- a = acceleration in m/s²
- e = transmission efficiency

Motor Selection and Sizing CONTINUED

A simplified expression for gravity torque and force that provides a reasonable estimation value is:

Rotary

$$T_g = \frac{0.0016\ W}{P\ e}$$

where:

T_g = gravity torque in N-m
W = weight of load in kg
P = pitch of transmission (rev/mm)
e = transmission efficiency

Linear

$$F_g = m_t\ g$$

F_g = total force in N
m_t = total mass in kg
g = acceleration from gravity

rms Torque

Obtaining the root-mean-square (rms) value of the required torque in an application is important because the heating of the motor is related to the square of the rms torque output of the motor.

Rotary

$$T_{rms} = \sqrt{\frac{\left(0.66\ T_\alpha^{\ 2} + T_f^{\ 2} + T_\omega^{\ 2} + T_g^{\ 2}\right)t}{t_{on} + t_{off}}}$$

where:

Trms = rms torque in oz-in (using 1/3-1/3-1/3 profile)
T_a = acceleration torque in N-n
T_f = friction torque in N-m
T_w = viscous torque in N-m
T_g = gravity torque in N-m
t_{on} = total move time in seconds
t_{off} = dwell time between moves

Linear

$$F_{rms} = \sqrt{\frac{\left(0.66\ F_a^{\ 2} + F_f^{\ 2} + F_g^{\ 2}\right)t}{t_{on} + t_{off}}}$$

F_{rms} = rms force in N (using 1/3-1/3-1/3 profile)
F_a = acceleration force in N
F_f = friction force in N
F_g = gravity force in N
t_{on} = total move time in seconds
t_{off} = dwell time between moves in seconds

Rotary Motor/Ball Screw Example

The specifications of the system are:

Ball-Screw Data

Diameter:	13 mm
Length:	500 mm
Pitch:	0.5 rev/mm
Efficiency:	90% (ball screw) 40% (lead screw)

Mechanical Data

Friction coefficient (μ):	0.05
Load:	4.5 kg
Orientation:	horizontal

Move Profile

Type:	1/3-1/3-1/3 trapezoid
Distance:	8 mm
Move time:	0.1 s
Dwell time:	0.1 s

Motor

Brushless:	BM75E

STEP 1. Determine move parameters

The peak speed (ω) and acceleration (α) of the motor required can be determined using the formulas:

$$\omega = \frac{1.5\,(25.13\ \text{rad})}{0.1\ \text{s}} = \frac{377.0\ \text{rad}}{\text{s}} = 3600\ \text{rpm}$$

$$\alpha = \frac{4.5\ \theta}{t^2} = \frac{4.5\,(25.13\ \text{rad})}{0.1^2} = 11310.0\ \frac{\text{rad}}{\text{s}^2}$$

Note: Verify that both values are within the specifications of the motor.

STEP 2. Determine motor shaft load inertia

The calculation of the inertia is dependent on the mechanics of the system. For the ball screw the inertia can be calculated by:

$$J_{screw} = (7.57\text{x}10^{-13})\ D^4\ L \quad \text{kg}-\text{m}^2$$

$$J_{screw} = 7.57\ \text{x}\ 10^{-13}(13\ \text{mm})^4(500\ \text{mm})$$
$$= 1.082\ \text{x}\ 10^{-5} \quad \text{kg}-\text{m}^2$$

where:

J_{screw} = screw inertia in kg-m^2
D = screw diameter in mm
L = screw length in mm

Motor Selection and Sizing CONTINUED

The inertia of the load using a ballscrew mechanism can be calculated using:

$$J_{load} = 2.55 \times 10^{-8} \frac{m_{load}}{P^2} \quad kg-m^2$$

$$J_{load} = 2.55 \times 10^{-8} \frac{4.5}{0.5^2} = 4.59 \times 10^{-7} \quad kg-m^2$$

where:

J_{load} = payload inertia (reflected) in kg-m²
m_{load} = payload in kg
P = screw pitch in rev/mm

From the results above, the inertia at the motor shaft is:

$$J_{system} = J_{screw} + J_{load} = 1.08 \times 10^{-5} + 4.59 \times 10^{-7}$$

$$J_{system} = 1.13^{-5} \quad kg-m^2$$

A motor that gives a good inertia match and meets the required motor speed of 3600 rpm is the BM75E, with an inertia of:

$$J_{motor} = 0.52 \times 10^{-5} \quad kg-m^2$$

Checking the inertia ratio (J_{system}/J_{motor}) = 2.2:1. The total inertia of the complete system is given by:

$$J_{system} + J_{motor} = 1.65 \times 10^{-5} \quad kg-m^2$$

Step 3. Calculate peak and rms torque

The acceleration (peak) torque, T_α , and friction torque, T_f , are now calculated using the system inertia values. The acceleration torque required can be estimated at:

$$T_\alpha = \left(J_{motor} + \frac{J_{screw}}{e} + \frac{J_{load}}{e}\right) \alpha$$

$$T_\alpha = \left(0.52 \times 10^{-5} + \frac{1.08 \times 10^{-5}}{0.9} + \frac{4.59 \times 10^{-7}}{0.9}\right) 11310$$

$$= 0.20 \quad N-m$$

The BM75E can provide 0.53 N-m of continuous torque and 1.41 N-m peak torque, which is much greater than the system requires. The element of friction torque, T_f , can now be derived using the friction coefficient (μ):

$$T_f = \frac{(W\mu)}{2\pi Pe} = \frac{(4.5)(9.8)(0.05)}{(6.283)(0.5)(1000)(0.90)} = 8.0 \times 10^{-4} \ N-m$$

Total peak torque required of the motor is estimated by:

$$T_t = T_\alpha + T_f = 0.20 + 8.0 \times 10^{-4} = 0.20 \ N-m$$

Knowing the total torque, the formula for rms torque is applied and determined to be:

$$T_{rms} = \sqrt{\frac{[0.66\,(0.20)^2 + (8.0 \times 10^{-4})^2]\,0.1}{0.2}} = 0.11 \ N-m$$

This is well within the motor's rating of 0.53 N-m.

Linear Motor Sizing Example

The following specifications summarize the system.

Machine Details

Friction coefficient (μ):	0.002
Load:	10 kg
Orientation:	horizontal
Air cooling:	1.36 bar (20 psi)
Carriage/motor mass:	5 kg

Move Profile

Type:	1/3-1/3-1/3 trapezoid
Distance:	350 mm
Move time:	250 ms
Dwell time:	275 ms

STEP 1. Determine move parameters

Using the 1/3-1/3-1/3 model:

$$a_{trap} = \frac{4.5\,x}{t^2} = \frac{4.5\,(0.35\text{ m})}{(0.25\text{ s})^2} = 25.2\,\frac{\text{m}}{\text{s}^2}$$

$$v = \frac{1.5\,x}{t} = \frac{1.5\,(0.35\text{ m})}{(0.25\text{ s})} = 2.1\,\frac{\text{m}}{\text{s}}$$

Note: Most systems utilize a sinusoidal acceleration profile instead of the more easily modeled trapezoidal for system considerations. Sinusoidal acceleration is modeled as:

$$a_{sine} = 1.5\,(a_{trap})$$

$$a_{sine} = 1.5\,(25.2\,\frac{\text{m}}{\text{s}^2}) = 37.8\,\frac{\text{m}}{\text{s}^2}$$

Note: Verify that all values are within the specifications of the system.

STEP 2. Determine moving mass
STEP 3. Calculate peak and rms force

$$m_{total} = m_{load} + m_{carriage/motor}$$

$$m_{total} = 10\text{ kg} + 5\text{ kg} = 15\text{ kg}$$

Breaking up the move profile into four segments, the fundamental equations for calculating forces during a trapezoidal move are:

1. $F_a = ma + F_f$
2. $F_{trav} = F_f$
3. $F_d = ma - F_f$
4. Cycle dwell time in seconds

Where:

F_a = force to accelerate the load
F_{trav} = force during traverse motion
F_d = force required to decelerate the load
F_f = force due to friction
ma = mass x acceleration

$$F_a = (ma) = (10\text{ kg})(25.2\,\frac{\text{m}}{\text{s}^2}) = 252\text{ N}$$

The friction force is determined by:

$$F_f = \mu\, m_{total}\, a_g = (0.002)(15\text{ kg})(10\,\frac{\text{m}}{\text{s}^2}) = 0.3\text{ N}$$

$$F_{peak} = F_a = 252\text{ N} + 0.3\text{ N} = 252.3\text{ N}$$

To compute rms or continuous force, dwell time must be known.

Applying the rms force equation from the previous example, F_{rms} is:

$$F_{rms} = \sqrt{\frac{(F_a)^2(t_\alpha) + F_f^{\,2}(t_{trav}) + (F_d)^2(t_{dec})}{t_{on} + t_{off}}}$$

$$F_{rms} = \sqrt{\frac{(252.3\text{ N})^2(83\text{ ms}) + (0.3\text{ N})^2(83\text{ ms}) + (251.7\text{ N})^2(83\text{ ms})}{(250\text{ ms} + 275\text{ ms})}}$$

$$F_{rms} = 141.7\text{ N}$$

The rms force of 142.4 N is used to select a linear motor. In this case, a BLM-203-A can provide up to 232 N of continuous force and 902 N peak force with 1.36 bar (20 psi) forced air cooling.