Calculating Linear Motor Requirements

In order to determine the correct motor for a particular application it is necessary to be familiar with the following relations.

**EQUATIONS OF MOTION**

Basic kinematic equation: \( x_0 + v_0 t = a t^2 / 2 \)

- \( a \) = acceleration (g’s)
- \( x \) = stroke (inch [m])
- \( t \) = time (seconds)
- \( v \) = velocity (in/sec [m/sec])
- \( g \) = gravitational acceleration (in/sec²[m/sec²])

A trapezoidal velocity profile is common with linear motors and the basic kinematic equation can be manipulated to yield results based on what is known.

When time and stroke are known:

When time and velocity are known:

When velocity and stroke are known:

Another common velocity profile associated with linear motors is the triangular velocity profile. As before, the basic kinematic equation can be manipulated to solve for this case.

![Triangular Velocity Profile](image)

When time and stroke are known:

When time and velocity are known:

When velocity and stroke are known:

**NEWTON’S SECOND LAW**

Newton’s Second Law provides a simple method of converting between forces, payloads, and accelerations. It states:

\[
F = ma
\]

where,

- \( F \) = Force (Lbs [N])
- \( m \) = payload (Lbs [kg])
- \( a \) = acceleration (g’s [g’s])
- \( g \) = gravitational acceleration (386in/sec² [9.81 m/sec²])

**Example:** Calculate the acceleration required to get a 3.2 Lbs [1.45 kg] payload horizontally at 1.3 g’s.

**Example:** Calculate the force required to accelerate a 5 in/sec² [12.7 m/sec²] payload horizontally at 1.3 g’s.
Linear Motors

**DUTY CYCLE**

The duty cycle of a motor is defined as the time the motor receives power during a cycle divided by the total time of the cycle. When a linear motor receives power for more than thirty (30) seconds, it is operating at a duty cycle of 100%.

\[
\text{Duty Cycle} = \frac{\text{time on}}{\text{time on} + \text{time off}} \times 100\%
\]

**Example:** During one cycle of operation a motor is on for 1 sec and off for 3 sec. What is the duty cycle of the motor for these conditions?

\[
\text{Duty Cycle} = \frac{1}{1 + 3} \times 100\% = 25\%
\]

Because duty cycles less than 100% allow time for the motor to cool, a lower duty cycle allows all linear motors, except steppers, to be run with more than three times their continuous current rating for a short period of time. Since force is proportional to current, motors operating at lower duty cycles can produce higher forces than when run continuously.

**EFFECTIVE CONTINUOUS FORCE**

The relation between the rated continuous force a motor can deliver and the effective continuous force it is capable of providing at a lower duty cycle is:

\[
F_C = \frac{F_{\text{D.C.}}}{\sqrt{\frac{100}{\text{D.C.}}}}
\]

**Example:** Calculate the effective continuous force of a motor that provides 197 Lbs [877 N] of force at a 30% duty cycle.

<table>
<thead>
<tr>
<th>English</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_{30} = 197 D.C. = 30%</td>
<td>F_{30} = 877 D.C. = 30%</td>
</tr>
<tr>
<td>F_C = 197 \sqrt{\frac{100}{30}} = 108 Lbs</td>
<td>F_C = 877 \sqrt{\frac{100}{30}} = 480 N.</td>
</tr>
</tbody>
</table>

**LINEAR MOTOR SELECTION PROCESS**

Following is the selection process for an application that requires a cog-free brushless linear motor. The first section provides customer requirements. The second section provides the calculations that are necessary to make the motor selection. The last section demonstrates the effect of reducing duty cycle and acceleration on motor selection.

**CUSTOMER REQUIREMENTS**

Application: Optical inspection (moving a single-axis optics carriage assembly)

- Stroke: 60 in [1.52 m]
- Duty Cycle: 100%
- Payload: 40 Lbs. [18.1 kg]
- Resolution: 3 micron customer-supplied encoder
- Load support: Customer-supplied bearings
- Motion Profile: Low force ripple required. Payload must move full stroke in 0.90 sec.

**Example:**

During one cycle of operation a motor is on for 1 sec and off for 3 sec. What is the duty cycle of the motor for these conditions?

\[
\text{Duty Cycle} = \frac{1}{1 + 3} \times 100\% = 25\%
\]

**EFFECTIVE CONTINUOUS FORCE**

The relation between the rated continuous force a motor can deliver and the effective continuous force it is capable of providing at a lower duty cycle is:

\[
F_C = \frac{F_{\text{D.C.}}}{\sqrt{\frac{100}{\text{D.C.}}}}
\]

Where

- \(F_C\) = continuous force [Lbs, N]
- \(F_{\text{D.C.}}\) = force at specified duty cycle [Lbs, N]
- \(\text{D.C.}\) = specified duty cycle [%]

**Example:** Calculate the effective continuous force of a motor that provides 197 Lbs [877 N] of force at a 30% duty cycle.

<table>
<thead>
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<tbody>
<tr>
<td>a = 4 x \frac{4}{386 , t^2}</td>
<td>a = 4 x \frac{4}{9.81 , t^2}</td>
</tr>
<tr>
<td>a = 4 x 60 \frac{386 \times (0.90)^2}{386 , (0.90)^2}</td>
<td>a = 4 x 1.52 \frac{9.81 \times (0.90)^2}{9.81 \times (0.90)^2}</td>
</tr>
<tr>
<td>a = 0.77 g's</td>
<td>a = 0.77 g's</td>
</tr>
</tbody>
</table>
Linear Motors

CALCULATIONS

Acceleration and force must be calculated to select the appropriate linear motor. Acceleration is calculated with the following formula:

\[ F = ma \]

so, \[ F = 40 \times 0.77 \]

\[ F = 30.8 \text{ Lbs} \]

\[ F = 137N \]

Force in calculated with the following formula:

\[ F = mag \]

\[ F = 18.1 \times 0.77 \times 9.81 \]

\[ F = 30.8 \text{ Lbs} \]

\[ F = 137N \]

MOTOR SELECTION

The linear motor that best meets the application requirements is the cog-free brushless linear motor model # LMCF08D. This motor’s continuous force is 33 Lbs. [147N] and has a maximum acceleration at this 100% duty cycle of 0.77 g’s.

EFFECTS OF LOWER DUTY CYCLES

Using Newton’s Second Law and leaving the payload unchanged, what acceleration is the LMCF08D motor capable of when operated at a 30% duty cycle?

Leaving the acceleration unchanged, what LMCF08D payload is the motor capable of moving when operated at 30% duty cycle?

INITIAL REQUIREMENTS CHANGE

What motor best meets the following requirements?

English | Metric
---|---
\[ F = ma \] | \[ F = mg \]

so, \[ F = 40 \times 0.9 \]

\[ F = 36 \text{ Lbs} \]

\[ F = 160N \]

Duty Cycle = 30%

Payload = 40 Lbs [18.1 kg]

Acceleration = 0.9 g’s

Using Newton’s Second Law and leaving the payload unchanged, what acceleration is the LMCF08D motor capable of when operated at a 30% duty cycle?

Since this is at a 30% duty cycle, the continuous force must be calculated. The

LMCF06D has a continuous force of 24.7 Lbs. [110N] and meets the acceleration and payload requirements of this application.
# Linear Motor Requirement Sheet

**Company** __________________________________________________

**Contact** __________________________________________________

**Title** ______________________________________________________

**Address** __________________________________________________

**City** _______________________________________________________

**State, Zip** __________________________________________________

**Address** ___________________________________________________

**Industry** ____________________________________________________

**Distributor** __________________________________________________

**District Office** ______________________________________________

**Describe the application and what you are trying to accomplish:**

__________________________________________________________________________________________________

__________________________________________________________________________________________________

__________________________________________________________________________________________________

**Estimated quantity needed** ________ **Need:** □ Immediate □ within 6 months □ within 12 months □ over 1 year

**Please provide as complete as possible:**

## A) Motor Type Preferred

- □ Don’t Know
- **Servo - Closed loop**
- □ Brushless Cog-free, no magnetic attraction
- □ Brushless Iron-core
- □ Brush
- **Stepper - Open Loop**
  - □ Single Axis
  - □ Dual Axis w/Air Bearing
  - **Light Load, Short Stoke Applications**
    - □ Moving Coil - Customer Supplied Bearing
    - □ Moving Magnet
  - **AC Induction**
    - □ Linear Induction Open Closed Loop
    - □ Polynoid - open loop, low duty cycle

## B) Stage Type Preferred

- □ Don’t Know
- **Single Bearing - open construction**
  - □ w/5 micron encoder standard
  - □ w/1 micron encoder optional
- **Extruded - industrial**
  - □ w/5 micron encoder standard
  - □ w/5 micron encoder optional
- **Enclosed - precision**
  - □ w/1 micron encoder standard
  - □ w/1 micron encoder optional
- **Cross-roller - high precision**
  - □ w/5 micron encoder standard
  - □ w/1 micron encoder optional
- **Air Bearing on Granite**
  - □ highest precision
  - □ highest precision
  - □ w/0.5 micron encoder standard
  - □ w/0.1 micron encoder optional
  - □ w/1 micron encoder optional

## C) Voltage Available

- □ 115 VAC Single Phase
- □ 230 VAC Single Phase
- □ 230 VAC Three Phase
- □ 460 VAC Three Phase

**Linear Induction Motors**

**NOTE:** Higher speeds require higher voltage.

## D) Environment

- □ ________ Degrees F
- □ ________ Degrees C
- □ Dusty
- □ Gritty
- □ ________

## E) Mounting

- □ Horizontal - Table
- □ Horizontal - Wall
- □ Vertical with _____ % Counterbalance
- □ Angled at _____ Degrees

## F) Position Resolution

- □ None Required
- □ 10 Micron = 0.0004 inch
- □ 5 Micron = 0.002 inch
- □ 1 Micron = 0.00004 inch
- □ Other _______
- □ Stepper Repeatability of _______

## G) Quote Additional

- □ Trap Amplifier - for point to point moves
- □ Sine Amplifier - for contouring moves
- □ Stepper Indexer Driver
- □ Motion Controller for _____ # of axes
- □ Stand Alone PC-based
- □ Linear Encoder w/resolution from above
- □ Motor Power & Hall Cable Length _______

## H) Cooling Available

- □ Convection - standard
- □ Forced Air
- □ Water

**Additional Notes (reference letter from above)**

__________________________________________________________________________________________________

__________________________________________________________________________________________________

__________________________________________________________________________________________________

__________________________________________________________________________________________________

__________________________________________________________________________________________________

__________________________________________________________________________________________________

---

**J-19**

**Baldor Motion Products**
Linear Motor Sizing Worksheet

To Size a linear motor for a horizontal application you need to know:
A) Maximum weights of moving load
B) Length of move and overall travel
C) Time to complete move in seconds
D) Velocity Profile - Triangular (for smallest size motor) or Trapezoidal

Procedure - Start with Step 1a or Step 1b

**Step 1a** Establish Acceleration Rate with Triangular Move Profile (circle units)

- Weight = _____________Lbs (Kg)
- Length of Stroke = ___________in (m)
- Move Time = ___________seconds
- Dwell Time = ___________seconds
- Max Overall Travel = ___________in (m)
- Velocity max = ___________in/sec or (m/sec)
- Acceleration = \[ \frac{4 \times \text{Stroke in [m]}}{g \times \text{Time in seconds}^2} \]
- For g use 386 for inches, 9.81 for metric.

Additional Acceleration Equations on Page 4 of this worksheet.

Acceleration Limits - If over 10g's not practical - need more time for move
Brushless < 10g’s  Induction < 1g  Stepper < 1g

**Step 1a** Establish Acceleration Rate with Trapezoidal Move Profile (circle units)

- Weight = _____________Lbs (Kg)
- Stroke During Accel = ___________in (m)
- Accel Time = ___________seconds
- Total Move Time = ___________seconds
- Dwell Time = ___________seconds
- Max Overall Travel = ___________in (m)
- Velocity max = ___________in/sec or (m/sec)
- Acceleration = \[ \frac{2 \times \text{Stroke During Accel in [m]}}{g \times \text{Time in seconds}^2} \]
- For g use 386 for inches, 9.81 for metric.

Additional Acceleration Equations on Page 4 of this worksheet.

Trap move may require RMS calculation.

Acceleration Limits - If over 10g's not practical - need more time for move
Brushless < 10g’s  Induction < 1g  Stepper < 1g
Linear Motor Sizing Worksheet continued...

**Step 2** Calculate Force Required to Accelerate the Load

**English**

F = mA  
Force Required = Weight of Load \(\times\) Acceleration (g's) 
Force to Accel the Load = _________ lbs \(\times\) _________g's 
Force to Accel the Load = _________ lbs

**Metric**

\(F = mA\)  
Force Required = Mass of Load \(\times\) Acceleration (g's) \(\times\) 9.81
Force Required = _________ kg \(\times\) _________ g's \(\times\) 9.81

**Step 3** Calculate Force Required to Move the System

Add static friction (i.e. stiction which would include wiper friction, etc.)

**English**

\(\text{Force} = (\text{Weight of Load} + \text{Slide}) \times \mu + \text{Stiction}\)
\(\text{Force} = (\text{Mass of Load} + \text{Slide}) \times \mu \times 9.81 + \text{Stiction}\)

\(\text{Force Required to Move the System} = \text{_______Lbs.}\)
\(\text{Force Required to Move the System} = \text{_______ N}\)

**Step 4** Calculate Force Required to Accelerate the System

Select motor with more force than the sum calculated in Step 2 & 3 (significantly larger if the acceleration is over 2 g's). Use the weight of the motor and the weight of the stage in your calculations below.

**English**

\(\text{Force} = (\text{Weight of Motor} + \text{Slide}) \times \text{Acceleration (g's)}\)
\(\text{Force} = (\text{Mass of Motor} + \text{Slide}) \times \text{Acceleration (g's)} \times 9.81\)

\(\text{Force Required} = \text{_______Lbs}\)

**Metric**

\(\text{Force} = (\text{Mass of Motor} + \text{Slide}) \times \text{Acceleration (g's)} \times 9.81\)

\(\text{Force Required} = \text{_______ N}\)

**NOTE:** Typical Friction Coefficient \(\mu\)
\(\mu = 0.16 \text{ Steel Lubricated V-way}\)
\(\mu = 0.005 \text{ Recirculating Ball Linear Bearing}\)
\(\mu = 0.5 \text{ Steel on Steel}\)
\(\mu = 0.05 \text{ Nonfriction Sliding}\)

**Step 5** Total the Force Required

Total the Force Required from Step 2, 3 and 4 and any additional force which a process may require (thrust). Verify the motor selected has a higher rating than calculated below.

**Force Required English**

from Step 2 _________ lbs
from Step 3 _________ lbs
from Step 4 _________ lbs
(may apply) _________ lbs of Additional Process Force
subtotal _________ lbs \(\times\) 1.2 Safety Factor

**Force Required Metric**

from Step 2 _________ N
from Step 3 _________ N
from Step 4 _________ N
(may apply) _________ N of Additional Process Force
subtotal _________ N \(\times\) 1.2 Safety Factor = _________ N

**NOTE:** If the total force required from Step 5 is:
(1) less than the continuous force of the stepper motor selected you can be finished
(2) for a brushless motor, and the force is between continuous and 3x continuous go to Step 6
(3) for an induction motor, and the force is between continuous and 5x continuous go to Step 6
Linear Motor Sizing Worksheet continued...

Step 6 Verify Motor Sizing for Intermittent Motion

It may be possible to reduce the size of the motor if the duty cycle is less than 100%. When there is significant time between moves the motor cools.

Duty Cycle \( \% = \frac{\text{Time On} + \text{Time Off}}{\text{Time On}} \times 100 \)

Force Continuous \( = \frac{\text{Force Required (step5)}}{\text{Duty Cycle}} \times 100 \)

\[ \text{lbs or N (circle one)} \]

NOTE:
1) When the Motor is Run more than 30 Seconds, it is at 100% Duty (motor type dependent)
2) Stepper Motors are rated at 100% duty (peak force = continuous force)
3) Linear induction motors are rated at 15% duty or continuous

Summary Fill in Summary if Known

<table>
<thead>
<tr>
<th>Known Information</th>
<th>Triangular Profile</th>
<th>Trapezoidal Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>English</td>
<td>Metric</td>
</tr>
<tr>
<td>Time and Distance</td>
<td>( \frac{4X}{386} t^2 )</td>
<td>( \frac{4X}{9.81} t^2 )</td>
</tr>
<tr>
<td>Time and Velocity</td>
<td>( \frac{2V}{386} t )</td>
<td>( \frac{2V}{9.81} t )</td>
</tr>
<tr>
<td>Velocity and Distance</td>
<td>( \frac{V^2}{386} (2X) )</td>
<td>( \frac{V^2}{9.81} (2X) )</td>
</tr>
</tbody>
</table>

Where
- Time: seconds
- Distance: inches
- Velocity: in/sec

Additional Information

☐ Holding Force required at End of Stroke
  ☐ One ☐ Both ☐ Amount________

☐ Size or Space Limitations

☐ Special requirements pertaining to control, mounting, etc.

Complete Velocity Profile

Attach any sketches or graphs.

Velocity Maximum _________ in/sec or m/s
Velocity Minimum _________ in/sec or m/s