PRECISION HYBRID STEPPER LINEAR TECHNOLOGY

INTRODUCTION:

One of the most common methods of moving a load from Point A to Point B is through linear translation of a motor by a mechanical lead screw and nut. This paper will assist and refresh your understanding of the basic principles associated with Hybrid Stepper Linear technology prior to selecting the system that best suits your application requirements.

We will begin by providing a brief overview of ball screw technology. NOTE that, although ball screw options are available with DINGS' Motion USA's linear actuators, this paper will focus primarily on acme style lead screw systems.

TECHNOLOGY COMPARISON -- ACME STYLE LEAD SCREWS VS BALL SCREWS:

Ball screws differ from Acme style lead screws in that ball screws translate motion through rolling friction (reference **Fig. 1, Ball Screw with Ball Nut** below).

Fig. 1, Ball Screw with Ball Nut

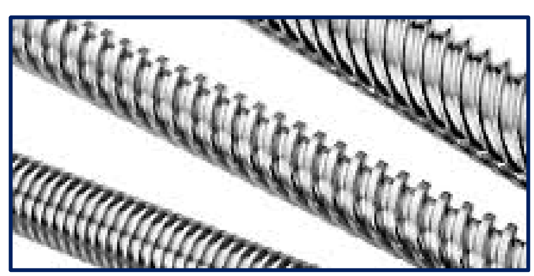
Ball screw technology has some basic advantages and disadvantages per the following:

- Advantages:
  1. Higher thrust capabilities
  2. Increased friction (80%-95%)
  3. Best for applications that require high duty cycles, high thrust, and high speeds

- Disadvantages:
  1. Can be back driven easily
  2. Much higher cost
  3. Much higher audible noise

Although acme style lead screws translate motion through sliding friction between the nut and screw, advanced materials have allowed for very low friction without use of external lubrication (reference **Fig. 2, Modified Acme Lead Screw** below).

Fig. 2, Modified Acme Lead Screw



Acme lead screw technology advantages and disadvantages are as follows:

- Advantages:
  1. Much lower in cost
  2. Very low audible noise
  3. May reduced or eliminate back driving (may be important in vertical applications)

4. Very fine leads

- Disadvantages:
  1. Greater friction between lead screw and nut (vs. ball screw technology), although advanced materials have minimized this drawback as noted above.

Acme lead screws are manufactured using a thread rolling machine. The machine uses rotating dies that apply high pressure force on blank shaft material to form thread profiles, thereby producing the lead screw.

AN EXPLANATION OF THE BASICS:

This section provides an understanding of the basic principles of lead screw technology. Please also reference the **Glossary** (Page 13) to support your understanding of the following:

- **LEAD vs. PITCH**
  Pitch is the axial distance between threads. Pitch is equal to lead in a **single start screw**. In contrast, lead is the axial distance the nut advances on one revolution of the screw. Lead is the term used to specify linear distance travelled for one revolution of the screw. The larger the lead, the more linear distance travelled per one revolution of the screw.

- **LOAD**
  Load is typically quantified as either lbs OR kg required to move, or pounds force (lbsF) or kilograms force (kgF) for thrust.

- **VELOCITY (V)**
  Typically quantified as velocity (V) in inches / second (mm / sec) required for a given application.

- **DISTANCE (d)**
  Defined as required move distance; typically quantified as either inches or mm.

- **TIME (t)**
  Time period required for a given distance that defines the velocity, acceleration (A), and deceleration needed to reach commanded position. Typically quantified in seconds.

- **HORIZONTAL OR VERTICAL (ORIENTATION) APPLICATION**
  Vertical orientation applications add the potential problem of backdriving when motor is powered off and lacks an installed brake. Vertical applications also have an additional gravity factor that must be considered when calculating load / force.

- **ACCURACY OF SCREW**
  Defined as the measurement over a given length of a screw. For example, (0.0006) inches / inch. Lead accuracy is the difference between actual and theoretical distance travelled based on the lead. For example, a screw with a (0.5) inch lead and (0.004) inch / foot lead accuracy rotated (24) times theoretically

moves the nut (12) inches. However, with a lead accuracy of (0.004) inch / foot, actual travel could range from (11.996) to (12.004) inches.

- **TOTAL INDICATED RUNOUT (TIR)**
  The amount of "wobble" around the lead screw centerline.

- **REPEATABILITY**
  Most motion applications place the most significance on the repeatability of a system (vs. accuracy of screw) to reach the same commanded position over and over again. For example, a repeatability of + / - (0.005) means that after repeated bi-directional commands to reach the same target position, the linear error will be no more than + / - (0.005) inch.

- **TENSION OR COMPRESSION LOADING**
  A load that tends to stretch the screw is called a tension load (reference **Fig. 3, Compression Loading** below). In contrast, a load that tends to "squeeze" or compress the screw is called a compression load (reference **Fig. 4, Tension Loading** below). Depending on the size of the load, designing the screw in tension utilizes the axial strength of the screw, versus column loading.

Fig. 3, Compression Loading

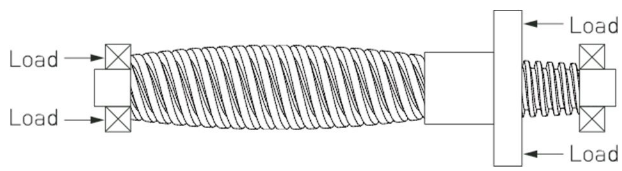
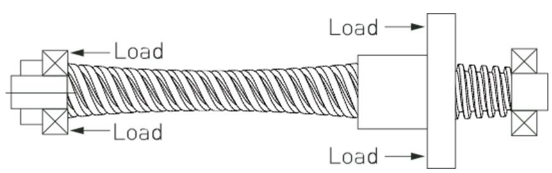
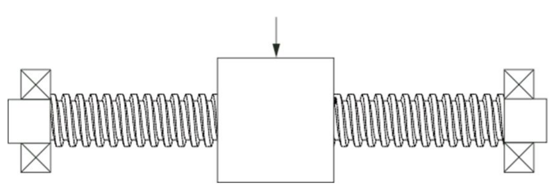


Fig. 4, Tension Loading



- **RADIAL LOAD**
  A load perpendicular to the screw (reference **Fig. 5, Radial Loading** below).
  This is not recommended unless additional mechanical support such as a linear guide is used.

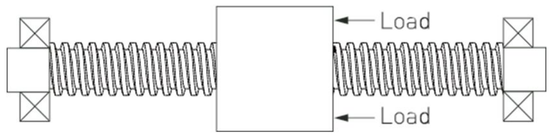
Fig. 5, Radial Loading



Radial Loading
(Avoid or Minimize)

- **AXIAL LOAD**
  A load exerted at the lead screw center line (reference **Fig. 6, Axial Load** below).

Fig. 6, Axial Load



Axial Center Loading (**BEST**)

- **STATIC LOAD**
  The maximum thrust load, including shock load, that should be applied to a non-moving screw.

- **DYNAMIC LOAD**
  The maximum recommended thrust load that should be applied to a screw while in motion.

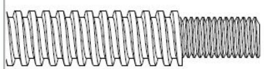
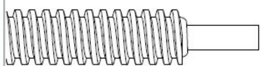
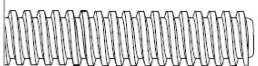
- **BACKDRIVING**
  Backdriving (or freewheeling) results from the load pushing axially on the screw or nut to create rotary motion. Generally, a nut with efficiency greater than 50% will have a tendency to backdrive. Selecting a lead screw with efficiency below 35% may prevent backdriving. The smaller the LEAD, the less likely backdriving will occur. Vertical applications are more prone to backdriving due to gravity.

- **TORQUE**
  The required motor torque required to drive only the lead screw assembly is the total of:
  1. Inertial Torque
  2. Drag Torque (Drag Torque = Friction associated with the nut and screw in motion)
  3. Torque to Move Load

- **LUBRICATION**
  NUT material typically contains a self-lubricating additive that eliminates the need to add lubricant to the system. The Teflon-coated screw option also lowers friction and may extend life of the system.

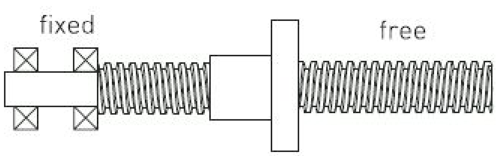
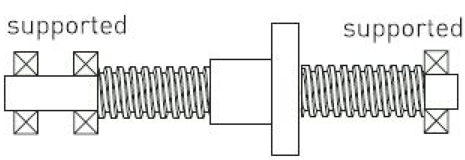
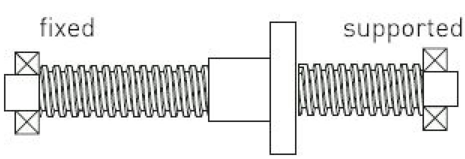
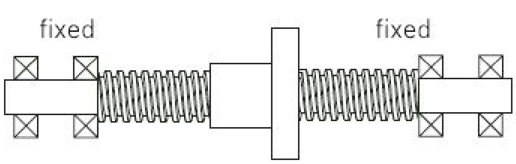
- **END MACHINING OF THE SCREW**
  Standard metric or English (UNC) options are available per **Fig. 7, End Machining Option Examples** below. End machining specifications are also available on request

Fig. 7, End Machining Option Examples

	Threaded end	Metric end: M4 x 0.7 mm thread to within 0.03"/ 0.76 mm of shoulder	UNC end: # 8-32 UNC-2A thread to within 0.03"/ 0.76 mm of shoulder
	Smooth end	Ø 0.1967" ± 0.001 Ø 5 mm ± 0.025	
	None	—	

- **FIXITY**
  Refers to the effect on performance (speed and efficiency) of the screw system by how the screw ends are attached and supported (reference **Fig. 8, End Fixity Methods** below).

Fig. 8, End Fixity Methods

Type of End Fixity	Relative Rigidity	Critical Speed Factor	Critical Load Factor
	Less Rigid	32	25
	Rigid	1.0	1.0
	More Rigid	1.55	2.0
	Most Rigid	2.24	4.0

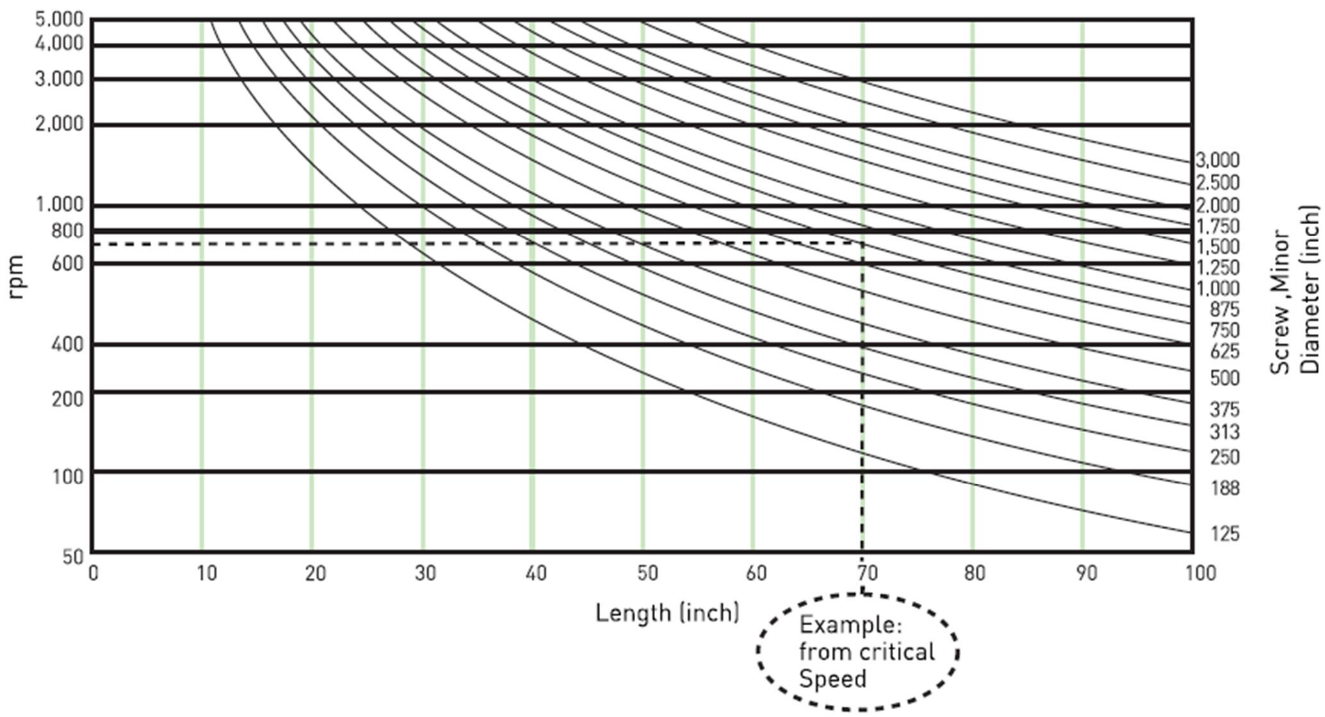
- **COLUMN STRENGTH**
  Refers to the effect on a screw loaded in compression; its limit of elastic stability can be exceeded and the screw will fail through bending or buckling.

- **CRITICAL SPEED**
  Critical speed is the rotational speed of the screw at which the first harmonic of resonance is reached due to deflection of the screw. A system will vibrate and become unstable at these speeds. Several variables affect how quickly a system will reach critical speed:

  1. Screw lead
  2. Rotational speed
  3. End fixity
  4. Thrust load
  5. Screw diameter
  6. Tension or compression loading

  For example, per **Fig. 9, Critical Rotation Speed (RPM) vs. Unsupported Screw Length for Various Screw Diameters (Inch)** below, a (3/4) inch diameter x (70) inch long screw has threshold for critical speed at 700 RPM.

Fig. 9, Critical Rotation Speed (RPM) vs. Unsupported Screw Length for Various Screw Diameters (Inch)



- **BACKLASH**
  Backlash is the relative axial movement between a screw and nut at standstill. It is normal for backlash to increase with wear over time. Backlash compensation or correction can be accomplished through the application of an anti-backlash nut (reference **Fig. 10, Anti-Backlash Nuts**, and **Fig. 11, Anti-Backlash Scenarios** below). In general, backlash is a concern with bi-directional positioning only.

Fig. 10, Anti-Backlash Nuts

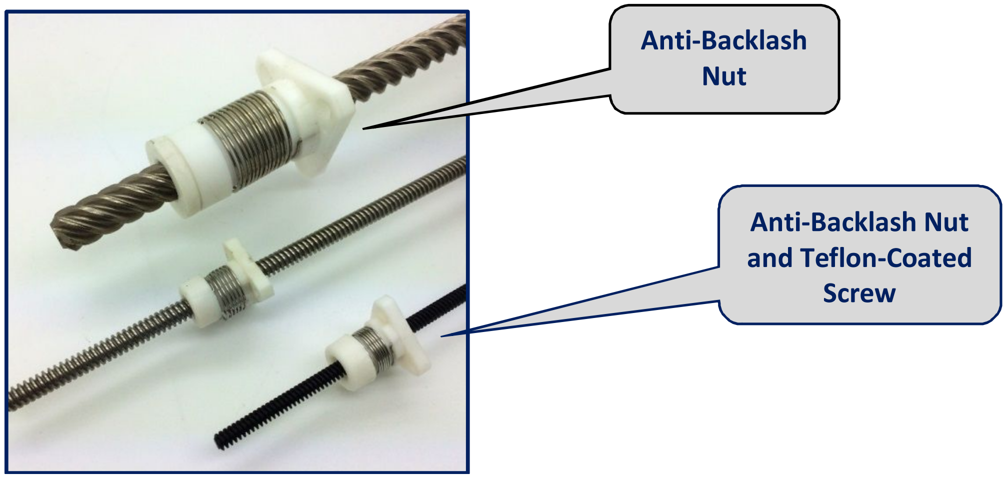
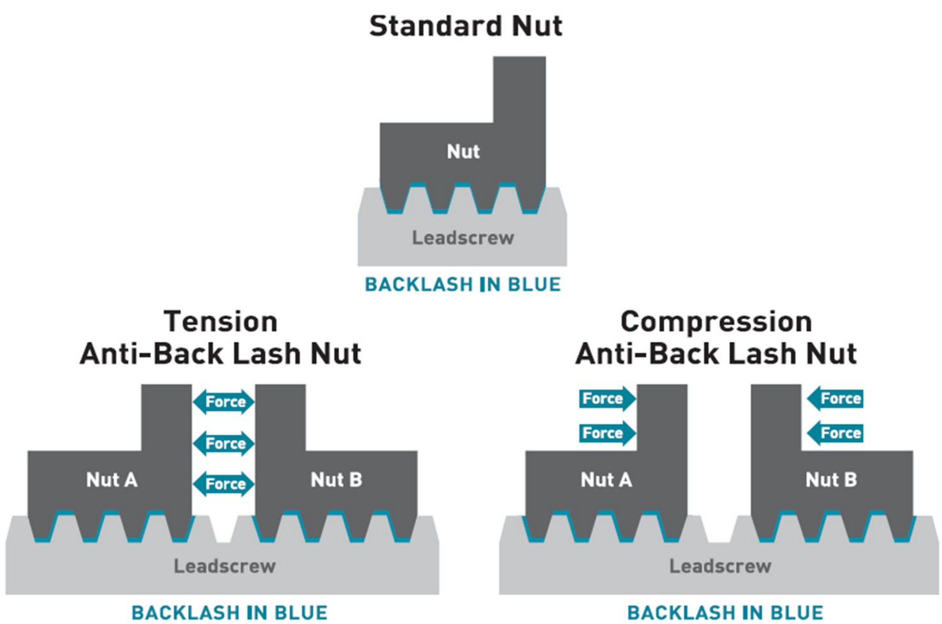


Fig. 11, Anti-Backlash Scenarios



<u>OVERVIEW – LINEAR MOTION SYSTEMS:</u>

- **LINEAR MOTION SYSTEM TYPES**
  There are three general types of linear motion systems (reference **Fig. 12, Linear Motion System Types**, and **Fig. 13, Summary: Linear Motion System Specifications** below).
  A. Non-Captive
  B. External Linear
  C. Captive

Fig. 12, Linear Motion System Types

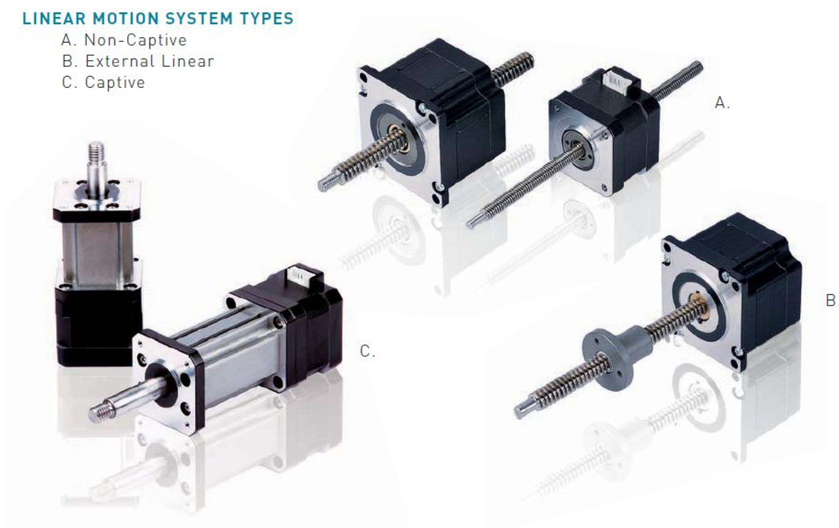
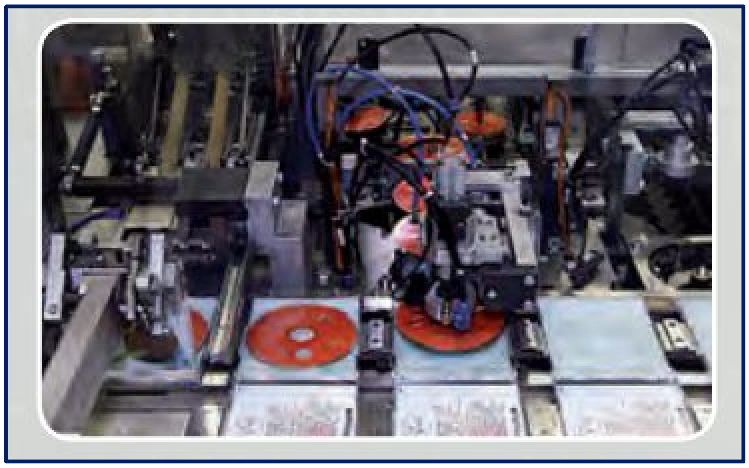


Fig. 13,

Nema Sizes	Available Versions	Motor Length & Available Currents (Voltage)	Max Thrust	Recommended Load Limit	Screw Lead Range
1.8 Degree Nema 8 Stepper		Single Stack (30mm): 0.5A (2.5V)	78N (17.5lbs)	43N (9.7lbs)	0.012" - 0.315" (0.30mm - 8.00mm)
		Double Stack (40mm): 0.5A (4.4V)	84N (18.9lbs)		
1.8 Degree Nema 11 Stepper		Single Stack (34mm): 0.5A (4.5V), 1.0A (2.2V)	230N (51lbs)	150N (34lbs)	0.025" - 0.400" (0.635mm - 10.16mm)
		Double Stack (45mm): 0.95A (3.9V)	340N (76lbs)		
1.8 Degree Nema 14 Stepper		Single Stack (35mm): 0.5A (6.6V), 1.0A (3.3V), 1.5A (2.2V)	450N (100lbs)	230N (52lbs)	0.024" - 0.500" (0.6096mm - 12.7mm)
		Double Stack (47mm): 0.5A (12.0V), 1.0A (6.0V), 1.5A (4.0V)	610N (135lbs)		
1.8 Degree Nema 17 Stepper		Single Stack (35mm): 0.5A (7.2V), 1.0A (3.6V), 1.5A (2.4V)	710N (160lbs)	230N (52lbs)	0.024" - 0.500" (0.6096mm - 12.7mm)
		Double Stack (49mm): 0.5A (11.0V), 1.2A (4.5V), 2.5A (2.2V)	900N (200lbs)		
1.8 Degree Nema 23 Stepper		Single Stack (47mm): 1.0A (6.4V), 2.0A (3.2V), 3.0A (2.1V)	1400N (315lbs)	920N (210lbs)	0.025" - 1.000" (0.635mm - 25.4mm)
		Double Stack (66mm): 1.0A (10.8V), 2.5A (4.2V), 4.0A (2.4V)	1800N (405lbs)		
1.8 Degree Nema 34 Stepper		Single Stack (80mm): 1.3A (12.0V), 3.0A (5.1V), 5.5A (2.85V)	2400N (540lbs)	2160N (485lbs)	0.100" - 1.000" (2.54mm - 24.4mm)

Summary: Linear Motion System Specifications



- **WHY CHOOSE ONE FORM FACTOR OVER ANOTHER?**
  1. What is the best mechanical fit for your application?
  2. How do you plan to attach the end of the screw?
  3. Is it necessary that the screw be secured from rotation?
  4. Does the application require an encoder?
  5. What is the stroke of the application?

- **ENVIRONMENTAL CONSIDERATIONS**
  Linear motion systems are typically designed to operate in dry and non-corrosive environments, unless an 'IP rated' product is specifically requested. Operating non-IP rated linear systems in dirty or corrosive environments significantly reduces product life.

- **TEMPERATURE**
  Very high or low temperatures may cause significant changes in nut fit or drag torque.

- **MAXIMUM DYNAMIC LOAD**
  Each Nema frame size motor has a mechanical load maximum that should not be exceeded, based on speed / torque curves for each frame size.

- **MOTOR AND DRIVE SELECTION**
  In order to select the right motor / lead screw combination, several factors should be considered:
  1. How much torque is required?
  2. What is the desired step angle?
  3. What are detent or holding torque requirements?
  4. Physical size restrictions?
  5. What type of driver (amplifier) does the application require?

- **TYPICAL SPECIFICATIONS**

Lead screw Material	303 Stainless precision cold rolled steel
Number of Starts	Single start acme thread (refers to the number of independent threads on the screw shaft)
Screw Coating	Standard is no coating; Teflon coating is optional
Standard Screw Accuracy (Lead Accuracy)	0.0006 in / inch
Screw Repeatability	+ / - .006 inch
System Repeatability (Motor and Screw)	Nominally equal to screw repeatability; motor variance adds + / - 6 micro steps
Screw Straightness (Measured as Total Indicated Runout – TIR)	.003 in / foot
Screw Efficiency	Ranges from 35% to 85%, dependent upon: • LEAD (screw efficiency increases with lead size) • Whether an anti-backlash nut is used with the screw
Operating Temperature	32 F to 200^{o}F

Screw Backlash	Depends upon screw lead (nominally +/- .005 in)
System Backlash	Includes screw, motor, and attached mechanics; refers to the sum of all backlash in the motion axis.
Nut Material	Polyacetal with lubricating additive. Freewheeling nut standard (anti-backlash nut available as an option).
Wear Life of Screw and Nut	Depends on load, speed, duty cycle, and environmental factors

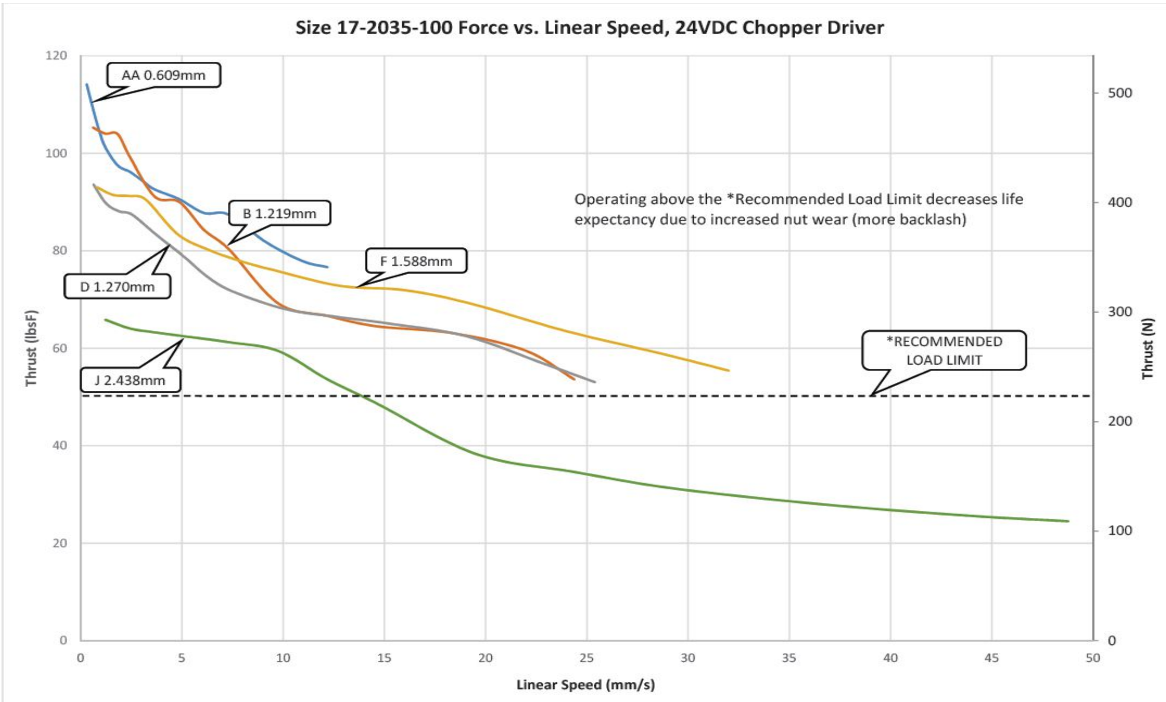
- **PRODUCT SELECTION CONSIDERATIONS**
  There are many inter-related variables to consider when selecting the right linear motion system for a given application. Application load and speed requirements will determine other variables such as size of motor, screw lead and ultimately, the voltage and current requirements of the electronic motor driver. Depending on application requirements, tradeoffs can be made with many variables as the system that meets performance, form factor, and cost specifications is finalized.

  Product selection should begin by quantifying the following basic variables:

  1. Thrust -- load that must be moved or pushed (see **Calculating Thrust for Linear Applications** below).
  2. Velocity
  3. Stroke -- distance to be travelled
  4. Required Acceleration -- time required to move from Point A to Point B
  5. Required Torque (for the ENTIRE linear motion system)
  6. Backlash -- how much backlash is acceptable in the system?
  7. Required Positional Repeatability
  8. Orientation -- Vertical or Horizontal orientation?

- **MORE ON FORCE AND SPEED REQUIREMENTS**
  As suggested above, Force and Speed requirements are two of the basic design considerations influencing selection of a linear motion system. After estimating the required thrust and choosing a Nema size that may fit your application, load speed and acceleration must be evaluated in order to choose an appropriate screw lead. Due to the nature of lead screws, output speed and output thrust achievable by a motor / lead screw combination are two inversely proportional variables (i.e., increasing the required thrust will lower the achievable speed for a given motor / lead screw combination). Therefore, a given system's maximum output force is lowered for applications that require higher speeds (reference **Fig. 14, Nema 17 Force vs. Linear Speed Curve** below).

Fig. 14, Nema 17 Force vs. Linear Speed Curve



- **CALCULATING THRUST FOR LINEAR APPLICATIONS**
  As already indicated above, Thrust is a key product selection variable applicable to linear motion systems. Therefore, it is useful to determine the amount of torque required from the motor to produce the Linear thrust needed for a linear application as part of the selection process. The following provides an overview of how Thrust / Force are used to calculate required motor rotary torque:

For a total Linear force of F_{total} (N), motor torque (T) required can be calculated using the following formula: $T = F_{total} \cdot \frac{L}{2\pi e}$

<u>Where:</u> T = Torque required from motor (Nm)
L = Screw lead (meters)
e = Efficiency of lead screw (0.2 – 0.4 for ACME lead screws)

<u>Example:</u>
For a total force of 12 lbs. (53.4N) and using a screw lead of 6.35 mm, and assuming that the screw efficiency is ~0.30:

F_{total} = 53.4N
L = 6.35mm
e = 0.30

$$T = F_{total} \cdot \frac{L}{2\pi e}$$

$$= 53.4\text{N} \cdot \frac{0.00635\text{m}}{2\pi(0.30)}$$

$$T = .18\text{Nm}$$

GLOSSARY

ACCURACY	The difference between the actual distance travelled versus the theoretical distance travelled based on the lead
AXIAL LOAD	A load that is exerted at the center line of the screw
BACKDRIVING	Freewheeling of the nut an screw as a result of the load pushing axially on the screw
BACKLASH	The relative axial movement between the screw and nut
CHOPPER DRIVE	A constant current drive is usually bipolar. The chopper drive gets its name from the technique of rapidly switching the power on and off to control motor current. A chopper drive allows a step motor to maintain greater torque of force at higher speeds.
COLUMN STRENGTH	The ability of a screw to withstand a load in compression
CRITICAL SPEED	The rotational speed of the screw at which the first harmonic of resonance is reached
DRAG TORQUE	The amount of torque to overcome the friction of a system
DYNAMIC LOAD	Load applied to the screw while in motion
EFFICIENCY	The ability of a mechanical system to translate an input to an equal output
FIXITY (END)	The method by which the ends of the screw secured or supported
LEAD	The linear travel at one revolution of the screw
LEFT HAND THREAD	Counter clockwise rotation
PITCH	The axial distance between threads
RADIAL LOAD	A load exerted at 90 degrees or perpendicular to a screw
REPEATIBILITY	The capability of a screw and nut system to reach the same commanded position continously
RESOLUTION	Incremental linear distance the actuator's (motor) output shaft will move per input pulse
RESONANCE	Vibration occuring when a system is a mechanical system is in an unstable range
RIGHT HAND THREAD	Clockwise rotation
SIDELOADING	Same as a radial load (very undesirable)
STATIC LOAD	Load applied to the screw at standstill
STRAIGHTNESS	Linear uniformity of a screw
TOTAL INDICATED RUNOUT	A measurement of the amount of straightness of a screw
TRAVEL PER STEP	Linear translation of one full step of the motor