WHICH SCREW?

Picking the Right Technology

Tolomatic

EXCELLENCE *IN MOTION*®

Contents

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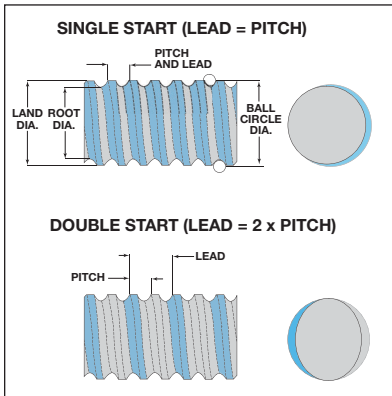EXCELLENCE *IN MOTION*®

Introduction

Many industrial linear motion systems employ a screw mechanism of some type to achieve a desired linear motion. The intention of this pamphlet is to supply an explanation of typical terminology used, explain the various types of screw mechanisms available, and provide a better understanding of what is involved in making the best screw selection as it relates to electro-mechanical actuation.

So, just what is a screw mechanism? A screw mechanism provides the means to produce linear motion by the rotation of either the screw or nut in an assembly. The screw is a cylindrical element upon which are formed threads; the nut is a matching component to the screw. Each component is capable of rotating independently upon the other. By restraining one element linear motion occurs.

A lead screw is a generic designation that in its broadest sense may be applied to multiple screw mechanisms. There are three primary types of screws used in linear actuators: acme, ball and roller. The differences are in the design of the thread shape along with the design and operation of a matching nut. These differences within each type of screw design will be detailed later in the following sections.

To provide an overall understanding of screw selection, it is first necessary to define common screw terminology and explain the different types of screws.

Screw Terminology

SINGLE START (LEAD = PITCH)

PITCH AND LEAD

LAND DIA.   ROOT DIA.   BALL CIRCLE DIA.

DOUBLE START (LEAD = 2 x PITCH)

PITCH   LEAD

Lead – The linear distance of travel that occurs with one revolution of the screw or nut. Measured in units per revolution such as "in/rev."

Pitch – The linear distance between threads. Pitch is not necessarily equal to the screw's lead when a screw has multiple thread starts. Measured in units such as "inch."

Turns – The number of revolutions required to travel a given distance. (i.e. 8 turns per inch)

Backlash – The amount of free movement between a screw and a nut.

Lead Accuracy – The possible variation in travel distance within a standard length of screw. Measured in unit per units such as "inch/foot."

Accuracy – The ability of a system to achieve the targeted linear position.

Repeatability – The ability of a system to achieve the same exact location in repeated attempts.

Static Load Rating – The maximum load that may be applied to a stationary screw and nut system without damage occurring.

Dynamic Load Rating – A value that is used in the life calculation for a screw and nut system. The maximum thrust load that may be transmitted by a screw and nut system.

Pre-load – The amount of tension or pre-applied force set into a bearing system to remove looseness (play) in the mechanical assembly. This applies both to screw and nut combinations as well as linear bearing assemblies. For ball screw systems, this reduces axial and radial play and increases system stiffness and repeatability.

Back-driving Force – The linear force or thrust required to rotate the screw or nut in a reverse fashion. For example, gravity in a vertical system may have the ability to back-drive a screw system creating torque and/or linear motion.

Rolling – A manufacturing process that forms thread profiles on a screw shaft through the use of high pressure forces in which rotating dies containing the desired thread profile are pressed against the blank shaft to displace material into the desired thread form.

Grinding – A very precise manufacturing process which may be used for creating thread profiles on a screw shaft by the removal of material using an abrasive wheel.

Critical Speed – The rotational velocity limit of the screw at which vibrations develop due to the natural harmonic frequency of the shaft. This is also commonly referred to as "screw whip" and is dependent upon the diameter and length of the screw between supports.

Duty Cycle – A percentage rating for an application that compares the amount of time running compared to the time at rest. An application that runs continuously would have a 100% duty cycle, where as an application that runs for 15 seconds and then rests for 45 seconds before completing another cycle would have a 25% duty cycle.

Screw Types
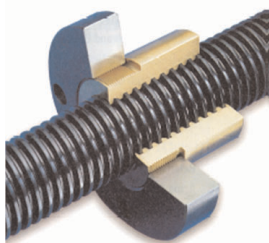
Photos courtesy of Nook Industries

Acme Screws

The acme screw, developed in 1895, utilizes a thread form having a generally trapezoidal tooth shape that is typically rolled into a steel shaft. The thread form itself is very strong and linear force is transmitted to a solid nut from the sliding surfaces on the flanks of the thread form.

The efficiency of a solid nut system, determined by the nut material and the lead, is relatively low and can range from 20% to 40%. This efficiency level often prevents the load or external forces from back-driving the screw mechanism, which can be an advantage. However, a disadvantage is the high amount of losses in the system that requires a larger motor torque input in comparison to other screw technologies.

Common nut materials include self-lubricating plastics or resins and metals such as brass or bronze. Non-metallic nut materials are generally higher in efficiency due to the lower coefficient of friction and often do not require the use of lubrication. Metal nuts such as bronze are capable of higher working loads but may require lubrication which can be an issue for some environments due to contamination.

The wear characteristics of acme nuts is dependent upon the nut material, environment and application requirments. The amount and rate of wear is generally not easy to predict due to the large number of variables. To compensate for the negative effects of nut wear, some manufacturers construct acme nuts using two halves that are biased to each other with a spring mechanism. Nuts of this design are commonly referred to as "anti-backlash" or "zero-backlash." It is important to note that these nuts may add friction to the system.

Acme screws are available in a wide variety of diameters and leads to match application requirements. A metric version of the acme screw is also available and commonly referred to as a trapezoidal screw. Although the tooth shapes are very similar, the two designs are not interchangeable due to a 0.5° flank angle difference.

Acme Screw Advantages:

- Generally lower in cost
- Quieter in operation
- May reduce or remove back driving
- Ideal for applications with
  - slower speeds
  - lower positioning requirements
  - lower duty cycles

Acme Screw Limitations:

- Solid nut design may wear and affect positioning
- Lower efficiency ratings require higher input torque
- Unpredictable service life
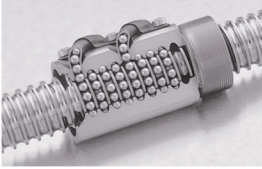- External factors such as environment can affect screw life

Screw Types

Photo courtesy of Thomson

Ball Screws

A ball screw utilizes a thread form that has a circular or ogival (gothic arch). The nut has a matched thread form allowing ball bearings that fit between the two grooves to transmit force and relative motion with high efficiencies, typically between 80-95%.

The ball bearings are allowed to roll and recirculate through one or several circuits in the nut as rotation and linear motion occurs. There are different designs of ball screw nuts that differ in the number of ball circuits and how the ball recirculation path is controlled. The ball bearing path is a critical factor in determining the maximum speed of the mechanism. Alternative designs, such as internal paths or end returns, offer minor advantages such as increased velocities or minimizing operating noise. However, most ball nut designs function similar in operation.

Ball screws are available in a wide variety of diameters, leads, and accuracies with both metric and imperial lead designs. A grade system was defined to classify the lead accuracies of ball screws and is regulated by ISO-3408. Ball screws are now commonly available in 5 grades as shown below.

GRADE	LEAD ACCURACY
1	6 μm / 300mm (~ 0.0002 in / ft)
3	12 μm / 300mm (~ 0.0005 in / ft)
5	23 μm / 300mm (~ 0.0010 in / ft)
7	52 μm / 300mm (~ 0.0020 in / ft)
10	210 μm / 300mm (~ 0.0080 in / ft)

The grade value of a ball screw can be used as a guideline for determining the lead accuracy of a specified system and is calculated in a cumulative fashion. These accuracy grades do not factor in any backlash specifications. Manufacturing

methods to achieve the noted grades are subject to the manufacturing capabilities; however grades 1 and 3 screws are almost always ground to achieve the high level of precision. Grinding, while precise, is also time consuming and a more costly manufacturing technique. Rolling is the most common method of manufacturing in the other grades of screws.

Backlash in a ball screw can be customized and this can be accomplished in a number of ways. A common way is to load each ball circuit with balls of a diameter that achieves the desired level of backlash. This method may also be used to achieve a preloaded system. Preloading can also be achieved by installing two nuts biased against one another and locked into position. Having two nuts on a single ball screw will not double the force capability of
the system.

Ball Screw Advantages:

- Higher thrust capabilities compared to a solid nut
- Longer life with predictable service life
- Increased efficiency (80% – 95%)
- Low backlash (from .0001 inch for low backlash to .005 inch typical)
- Ideal for applications that require high duty cycles, high thrust, and high speeds

Ball Screw Limitations:

- The ball nut can easily be back-driven depending upon lead
- Higher initial cost compared to an acme screw
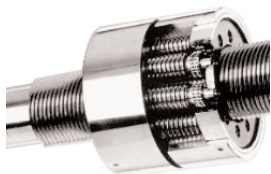- Often generates more noise than an acme screw

Screw Types

Photo courtesy of American Roller Screw

Roller (planetary) Screw

A roller screw thread form is generally triangular in shape and transmits force through a matched set of multiple threaded rollers in the nut. These rollers are allowed to rotate within the nut while contacting the thread form of the screw. The roller nut has a set number rollers that provide significant contact area with the screw, resulting in very high force transmission capabilities and a longer life compared to ball screws of a similar diameter.

Like ball screws, roller screws have a good efficiency rating because they are designed with rolling elements as compared to the sliding elements of acme screws. Due to the increased areas of contact, the efficiency may be slightly lower than a ball screw and commonly ranges from 70% to 90%.

Roller screws, like ball screws, are produced within the ISO-3408 grade system so they share similar lead accuracy considerations. Roller screws are most commonly ground to provide continuous contact area, smooth motion, and high thrust outputs. However, some roller screws are now being precision rolled to offer lower cost solutions, with some possible sacrifice in performance.

Roller Screw Advantages:

- Very high thrust capabilities
- Extremely long life
- Higher speed and acceleration rates possible
- Low maintenance
- High efficiency

Roller Screw Limitations:

- Highest cost of three screw types
- In vertical applications, the screw can be back-driven or free fall with loss of motor torque
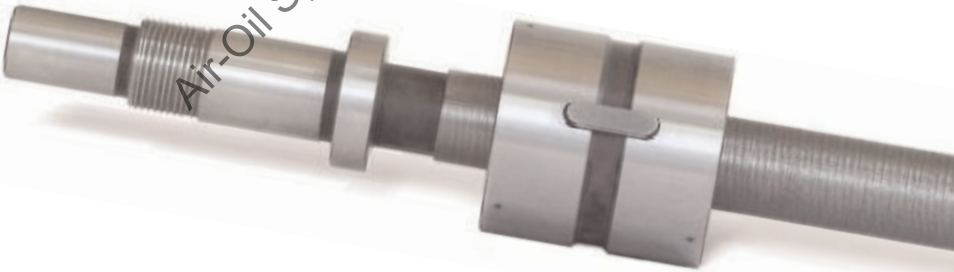- Nut assembly has a larger outside diameter

Photo courtesy of Nook Industries

Lead Screw Selection Considerations

Thrust

The amount of thrust or axial force that is required by the application is one of the most important factors when selecting a screw mechanism. A higher thrust requirement will normally relate to an increase in the screw's diameter because a screw is similar to a column that is subject to both compression and tension loading. During a compression load, it is undesirable for the screw to bow or deflect. During a tension load, it is important that the column can support the load without failing. The theoretical formula to calculate the column strength in pounds is:

$$Pcr = \frac{14.03 \times 10^6 \times F_C \times d^4}{L2}$$

WHERE:

Pcr = **Maximum load**

Fc = **End fixity factor**

      .25 **for one end fixed, one end free**

      1.00 **for both ends supported**

      2.00 **for one end fixed one end simple**

      4.00 **for both ends rigid**

d = **Root diameter of screw**

L = **Distance between nut and load carrying bearing**

For linear actuator applications, there are two different thrust values that should be considered: peak thrust and continuous thrust. Peak thrust is normally present during a shorter period of time, such as the acceleration or deceleration of a high speed move profile or during the pressing or pushing of a product. A peak thrust may be greater than 3 to 5 times the continuous thrust or equal to the continuous thrust, depending upon the application.

The continuous thrust is a calculated average value that is referred to as an RMS value, or root mean square. The continuous thrust can also be a thrust that is maintained over a longer stroke, such as one would find in a volumetric piston pump application. With either peak or continuous thrust values, it is important to verify that the screw shaft will be able to support the applied forces. The continuous thrust is also an important variable in determining the estimated L10 life of the ball or roller screw, which is discussed in a different paper.

Another important factor is the nut design and nut material. For an acme screw, the material selection of a composite resin or metal will have a significant impact on available thrust. For example, an inch diameter acme screw with a 0.125 inch lead, the resin material nut may have an operating load rating of 625 lbs, as compared to 1,250 lbs for a bronze nut.

In a ball screw, the nut design and lead may affect the quantity and diameter of the ball bearings recirculating within the nut. With an increase in number of balls inside the nut, the number of thrust supporting contact points increases, thus increasing the thrust capability. As a comparison, consider two inch ball screws, the first having a 0.200 inch lead and the second having a 0.500 inch lead. The first screw has a dynamic load rating of 973 lbs and is designed as a single start screw, two ball circuits with 40 balls in each circuit. The second screw has a dynamic load rating of 786 lbs and is designed as a double start screw, two ball circuits with 30 balls in each circuit. In these two screws, the number of balls in the nut is playing a significant role in determining the thrust capability.

The number of rollers in the roller nut have a similar effect on its thrust capacity.

Lead Screw Selection Considerations

The screw's lead also affects the linear actuator system's thrust capacity. To calculate the linear thrust output of a screw mechanism, the following formula can be used:

$$\text{Torque} = \frac{(\text{Thrust required} * \text{Screw lead})}{2\pi * \text{efficiency}}$$

Example: Produce 100 lbs of continuous thrust using an inch acme screw with a lead of 0.2 inches and an efficiency of 40%. Using this formula, you would need an input torque of 8 lb in. If the lead was changed to 0.5 inches, you would need an input torque of 20 lb in.

$$8 \text{ lb in} = \frac{(100 \text{ lb} * 0.2 \text{ in})}{2\pi * 0.4} \qquad 20 \text{ lb in} = \frac{(100 \text{ lb} * 0.5 \text{ in})}{2\pi * 0.4}$$

The above calculations assume a system with zero losses. There are additional forces that need to be accounted for such as bearing preloads, gravity, friction and breakaway torque into the equations above. The simplest and easiest way to account for all forces is to use a sizing tool such as Tolomatic's sizing and selection software.

Speed

Speed is usually the second most important parameter to evaluate when selecting a screw. All screw mechanisms have a critical velocity — the rotational velocity limit of the screw after which vibrations develop due to the natural harmonic frequency of the shaft. This is also commonly referred to as "screw whip" and is dependent upon the diameter and length of the screw between supports. It is important to note that the critical velocity of a screw is not dependent upon the orientation (horizontal, vertical, etc).
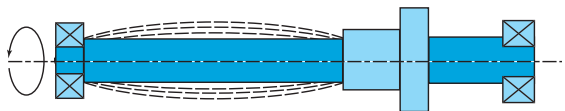
A theoretical calculation for critical velocities exists when both ends of the screw are fixed into bearings, however it is recommended that the maximum velocity is less than 80% of this calculation.

$$N = \frac{4.76 \times 10^6 \times d}{L^2}$$

WHERE:

N = Critical speed

d = Root diameter of screw

L = Length between bearing supports

In ball nuts, bearings run along rolled or ground tracks between the screw and nut and through recirculation mechanisms. As the screw increases in speed, the ball velocities increase as well to a point where they become projectiles as they pass through the ball circuit. This complicated action, which needs to be controlled, can also limit speed.

All lead screw designs maintain a direct ratio between the input rpm and output linear velocity, which is dependent upon the lead. In applications where high speeds are required, a larger lead can be specified that lowers the input rpm of the screw. Below is an easy formula to calculate the required RPM for screw mechanisms:

$$RPM = Linear\ Velocity * Lead \quad 300\ RPM = \frac{10\ in}{s} * \frac{60\ s}{m} * \frac{0.5\ in}{rev}$$

Accuracy and Repeatability

It is important to understand the difference between accuracy and repeatability, as these two terms are often used interchangeably. If misapplied or misunderstood, significant and unnecessary costs can result.

Lead Screw Selection Considerations
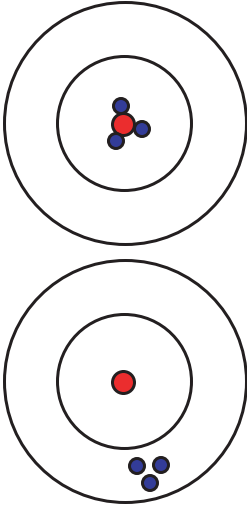
Accuracy is the ability to achieve the desired exact location within a tolerance level. To achieve accuracy, a ball screw must be selected with the lead accuracy required for the application. Grades with the highest accuracy values in almost all cases will be the most expensive.

Repeatability is the ability to achieve the same location upon multiple attempts. Many applications will not require a high degree of accuracy but will very likely require a high level of repeatability. It is possible for ball and other types of screw technology to be highly repeatable without being highly accurate.

Ball or roller screws, because they do not wear like acme nuts, maintain a higher level of repeatability. Backlash, the next area of discussion, is also an important consideration for bi-directional repeatability.

Backlash

Backlash is the amount of linear movement between the screw and nut without rotation of the mechanism. This can be a critical factor for applications that require stiffness or accuracy and repeatability from both directions of travel. Example: you are traveling in a positive direction to an absolute position of 10.000 inches, which you successful achieve. When you reverse directions and go to an absolute position of 5.000 inches using the motion controller, the actuator may only be at 5.010 inches if you have a 0.010 inch backlash.

External forces that are acting on the actuator can also play a role in determining if backlash will be a factor for your application. In a vertical application, gravity will normally keep a downward or negative force on the actuator, thus eliminating

the possibility of seeing the effects of backlash. In some applications, an external force may be acting against the linear actuator, such as products on a conveyor belt or a pneumatic cylinder, removing the backlash effect.

Most solid nuts will wear over the course of life and increase in backlash. Some solid nuts are available with anti-backlash mechanisms. However it is important to note that wear still occurs in the anti-backlash versions and does affect accuracy over the life of the nut.

Ball nuts are available with standard (commonly .005 - .015 inch) and lower backlash technologies. Typically, there are two methods to achieve lower backlash ball nuts. The first employs oversized balls being loaded into the nut that lowers the backlash to a specified level. This method is very common and the most cost effective. The second method uses two nuts that are biased against one another. This method is more expensive and also may increase the overall nut length, which may affect the actuators dead length. Backlash characteristics of roller screws are between .0005 - .0015.

Resolution

Resolution is normally related more to the motion controller, motor and feedback devices in a linear actuator system. Preload, break-away torque and the torsional twist of long screws may also play an important factor if moving small increments, such as <0.001 inch. It is important to let the vendor of the components know your expected accuracy and repeatability requirements with the addition of your smallest incremental move. The lead on the lead screw also has a major effect in the system resolution. The finer the screw lead selected will provide a system with higher resolution. This is important to note because your system solution may require a

Lead Screw Selection Considerations

lower resolution feedback device or lower cost motor and drive if a higher resolution screw is installed. Keep in mind that the screw's lead will also affect the maximum linear speed and linear force output.

As an example, consider a lead screw that has a 0.5 inch lead as compared to a 0.2 inch lead. Looking at the linear travel per degree of motor rotation, there is a considerable difference that may result in a lower cost motor and drive solution.

0.5 in lead — 0.0014 in / deg   0.2 in lead — 0.0005 in / deg

The following chart shows the overall comparisons of using the types of screw technologies in electromechanical actuators and how it affects the performance characteristics of the actuator.

SCREW TYPE			
CHARACTERISTIC	**LEAD**	**BALL**	**ROLLER**
Stroke	Medium	Medium	Short – Medium
Speed	Slow	Medium	Medium – High
Thrust	Medium	Medium	High
Accuracy	Medium	Medium – High	High
Backlash	Medium – High	Low – Medium	Low
Repeatability	Low – Medium	Medium – High	High
Resolution	Medium – High	Medium – High	Medium – High
Back driven	Difficult	Moderate	Moderate

Summary

It is important to understand the requirements of the application when selecting a screw and nut for an application in a linear motion system.

First, determine the answers to the following questions:
Load:
- Are there multiple components?
- What are the masses?
- Where are the centers of gravity?

Orientation:
- How will the actuator be positioned?

Move Profile:
- What is the total length of travel?
- What is the fastest move profile?
- What is the duty cycle or frequency of the move profile?
- How accurate does the move need to be?
- How repeatable does the move need to be?
- Will backlash be an issue?

These decisions will not only influence the choice of screw technology, but the total system performance.

Acme screw applications
The contact surfaces of the acme screw system are solid surfaces sliding against each other and therefore offer quiet operation compared to recirculating elements of a ball screw mechanism. Therefore, applications that require near silent operation will benefit from an acme screw and nut selection.

Acme screw and nut systems are also the most economical, but there is a trade off associated with a lower cost. Acme screws are the least efficient of the screw

Summary

types. They have a comparatively high rate of wear and as a result can experience the highest amount of backlash. Acme systems would be a good choice for applications where cost is an important factor and accuracy or repeatability is of a lesser concern.

Since most acme screws will not back drive, acme systems can also be a good choice in applications where back-driving is undesired, such as a vertical installation. Slow speed, lower positioning requirements and manual or hand crank would be other good choices for acme screw/nut systems.

Ball screw applications

Ball screw systems are available in a wide variety of diameter and lead combinations and are graded for their lead accuracy. They are higher in cost than acme screw systems but offer higher thrust capacity, longer life, higher accuracy, and consistent backlash.

Ball screw systems are good for applications that require high loads and tight positioning. The industry offers a wide degree of flexibility in screw diameter and lead combinations. Low friction, relatively long life, and consistent performance are attributes of ball screw systems. However, the increased efficiency can make them more apt to back driven. When used in vertical applications, the use of a brake or other mechanism may be required to assure appropriate function and safety. Ball screw systems are widely used and are the workhorse of linear motion systems.
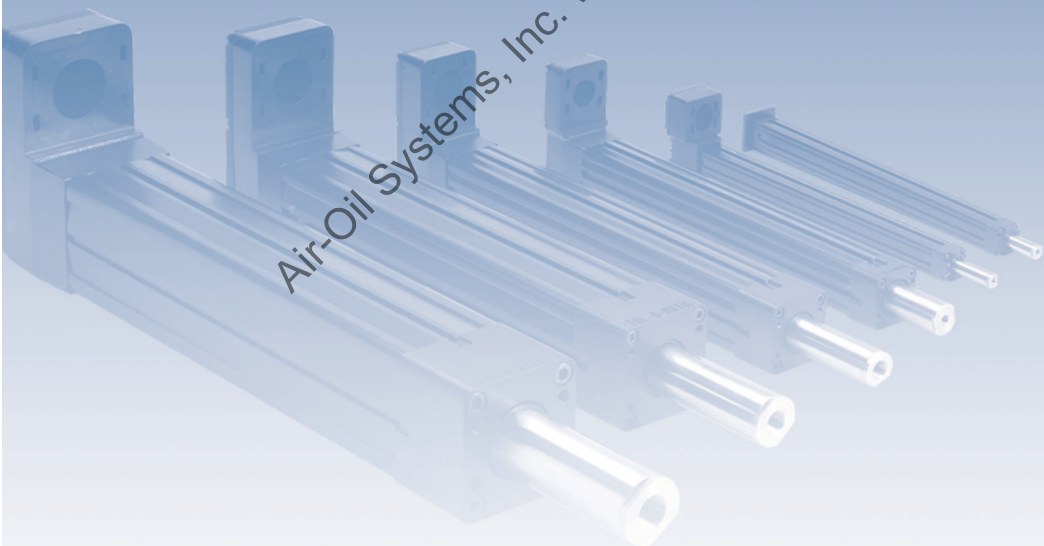
Roller screw applications

Rollers screws have a larger surface area of nut rollers in contact with the screw shaft threads. They provide higher load capabilities than a ball screw of the same diameter. The roller screw manufacturing process is very detailed and labor intensive, so the relative cost is considerably higher than ball screws. Roller screw technology is well suited for applications where extremely high forces in a small envelope are required or if an application requires an extended life. If an application requires high force or long life, roller screw technology can be a good choice.

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