# 10 Steps To Achieve Optimal Ball Screw Selection

## Executive Summary

Ball screw assemblies translate rotational motion to linear motion or vice versa. They are widely used to guide, support, locate and accurately move components and products in a wide range of automation applications, ranging from small laboratory fluid pumps to large overhead gantry systems. Specifying the right ball screw for a given application will ensure machine accuracy, repeatability and life while minimizing the total cost of ownership. This whitepaper provides an overview of ball screw assemblies and the factors that motion system designers must consider to ensure optimal application performance.

## Ball Screw Basics

A ball screw assembly consists of a ball screw and a ball nut with recirculating ball bearings. (Figure 1) The interface between the screw and the nut is made by ball bearings that roll in matching forms in the ball screw and ball nut. The load on the ball screw is distributed over a large number of ball bearings so that each ball is subjected to a relatively low load. Because of the rolling element design, ball screw assemblies have a very low coefficient of friction, which equates to high mechanical efficiency.

The key difference between ball screws and lead screws, which are also considered for comparable applications, is that ball screws use a recirculating ball bearings screw to minimize friction and maximize efficiency. This makes ball screws more expensive than lead screws, but their ability to carry higher loads, achieve faster speeds and achieve predictable life makes them well worth their added cost for many applications. Also, because the ball bearing assembly typically provides mechanical efficiency greater than 90%, the higher cost is often offset by reduced power requirements. For end-users, the increased load capacity, longer life and predictable reliability of ball screws are advantages over lead screws.

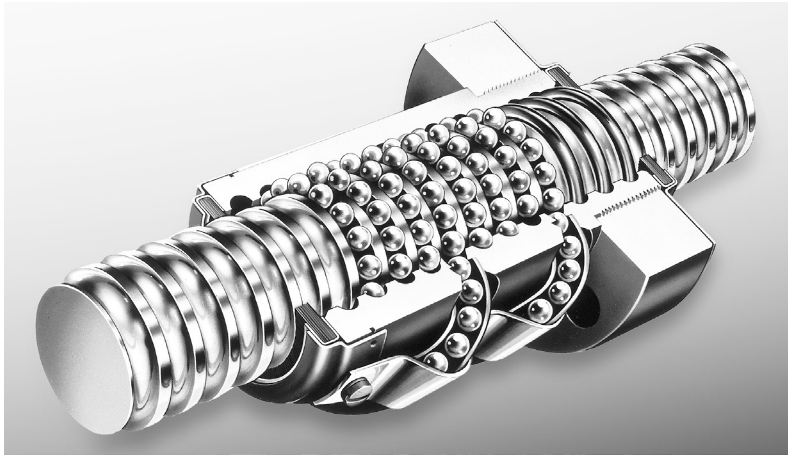

*Figure 1. Ball Screws use recirculating balls to minimize friction, which provides more than 90% mechanical friction.*

Selecting the right ball screw assembly for a specified load capacity and precision is an iterative process. It starts with determining the load to be moved, the required velocity, and the positioning accuracy and repeatability desired. From there you can calculate the diameter, lead and load capacity of the ball screw assembly to drive your application, and once you have that, you can refine the selection based on considerations of durability over the lifecycle, mounting configuration, and environmental conditions.

The following are 10 steps that will lead you to an optimal ball screw selection:

1. Establish load and velocity requirements.
2. Determine application life expectancy.
3. Determine accuracy requirements.
4. Determine repeatability requirements.
5. Assess mounting issues.
6. Determine whether you should be using the ball nut in tension or compression mode.

7. Consider vibration and harmonic challenges.
8. Explore other design possibilities.
9. Understand handling and maintenance requirements.
10. Take full advantage of online selection and configuration tools.

We explore each step below.

**1. Establish load and velocity requirements**

Although you may end up modifying the load or velocity specifications based on considerations of available component options, these are always application dependent.

Ball screws are available to handle high thrust loads upwards of 337,213 lb (1500 kN) of dynamic capacity using a Ø6.3-in. (160 mm) ball screw assembly with efficiency typically greater than 90%. They can achieve velocities up to 4500 RPM.

**2. Determine application life expectancy**

Life expectancy should be defined based on the operational profile – how many hours per day, days per week and weeks per year the ball screw will be run – and the overall life requirement for the ball screw.

For more complex applications, you also have the option to build a complete motion profile. Each segment of the motion profile requires entry of the speed at the beginning of the segment, the speed at the end of the segment, the segment time and the torque during the segment.

Calculate the assembly life using the dynamic load rating specified for each ball nut provided in Figure 2. All ball nuts with curves that pass through or are above the plotted point are suitable for the example. The suitable life expectancies shown in this graph are not to exceed the maximum static load capacity as given in the rating table for the individual ball nut assembly. In the example shown by the arrows in Figure 2, when application life expectancy (total travel) desired is 2 million in. (50.8 million mm), the maximum normal operating load is 10,000 lb. (44,500 N).

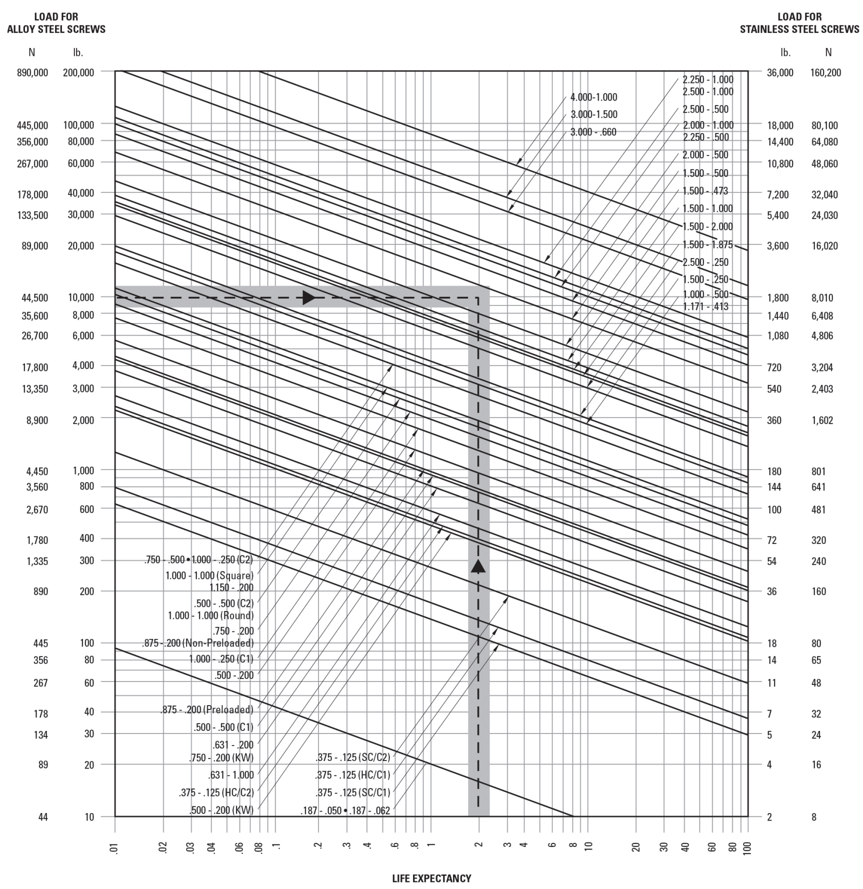


*Figure 2. Assembly life expectancy.*
*C1 = Single Circuit C2 = Double Circuit SC = Standard Capacity HC = High Capacity*

**3. Determine accuracy requirements**

Lead accuracy is the most common measure of ball screw accuracy. Lead refers to how far a non-rotating ball nut will travel with a single 360-degree turn of the screw. Lead accuracy is measured as the permissible travel variation (actual position vs. theoretical position) per foot, in a ball screw built on an inch scale or per 300 mm in a metric product.

Ball screws are available in two tolerance levels: transport (T-Grade) and positioning (P-Grade.) T-Grade is the lower level with precision typically ±50 µm/300 mm or higher, and designers specify it primarily for applications requiring simple translation of a load from one point to another. When applications require knowledge of the absolute position of a load at every point along the stroke without implementing external feedback assemblies, they specify the higher-precision P-Grade accuracy, which typically provides accuracy of ±23µm/300 mm or lower.

The accuracy designation also defines the overall accumulation of positional error. Transport-grade error is cumulative and linear, whereas precision-grade error is controlled and constrained. Transport-grade ball screws tend to be less expensive than precision grade. Figure 3 compares transport- and precision-grade variations over the usable length of the ball screws.

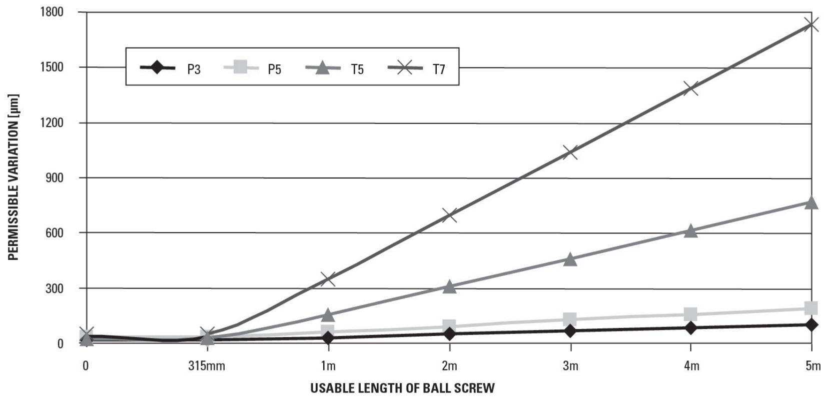


*Figure 3. Permissible travel variation over usable length.*

### 4. Determine repeatability requirements

Where accuracy is the measure of how closely a system approaches a command position, repeatability is the measure of its ability to return to a designated location during operation. Impacting repeatability is the free movement between the nut and the screw, known as "backlash," which can be measured axially or radially.

Ball screw backlash is largely a function of ball bearing diameter. To measure axial backlash, secure the screw from movement and axially push and pull on the ball nut while measuring its movement with a dial indicator. Or, put a dial indicator on the ball nut in the system and drive it 1 in. forward and back to the original position. The variation from zero is the backlash. Repeatability is the quantitative value of that variation, and ball screws are known for their low backlash and thus excellent repeatability.

Preloading the nut can control backlash. With skip-lead preload, the lead is offset within the ball nut to provide a precise preload. This type of preload is typically used where both repeatability and high stiffness are needed. Double-nut adjustable preload involves the use of a compression spring to axially load two ball nuts against each other. It is typically used for positioning applications where repeatability is critical.

Where no preload is used, axial play is present between the screw and nut, typically 0.002 to 0.008 in. (0.06 to 0.2 mm) depending on the size. Preload is typically not used for transport or vertical applications. A non-preloaded ball nut has internal clearances between components, meaning that backlash exists. A preloaded ball nut, however, has no axial clearance, which eliminates backlash and subsequently increases stiffness.

Preloading also increases the torque required to turn the screw and is measured by the percentage of preload to dynamic capacity. A ball nut with a dynamic capacity of 1500 lb. and a preload rating of 10% has a 150 lb. internal preload. Precision thread ball screws are generally used without pre-load. Although preloading a ball screw improves repeatability by removing backlash, it does not affect accuracy.

Preloaded ball nuts are available on select precision screw products. They cost more than non-preloaded nuts due to complexity, additional machining, assembly and verification/measurement. Ball screw assemblies can be preloaded with double or single nut configurations. There are three major types of preload – single nut oversized ball (4-point contact), single nut skip lead (2-point contact) and double-nut (2-point contact). (Figure 4) Single-nut preload maintains the smallest package size while maintaining full load capacity. Skip lead ball nuts have half the capacity of similar-sized single nuts as only half the ball bearings are loaded in each direction. Double-nut preload assemblies have the same load capacity as a single-nut because only one ball nut is loaded in each direction.

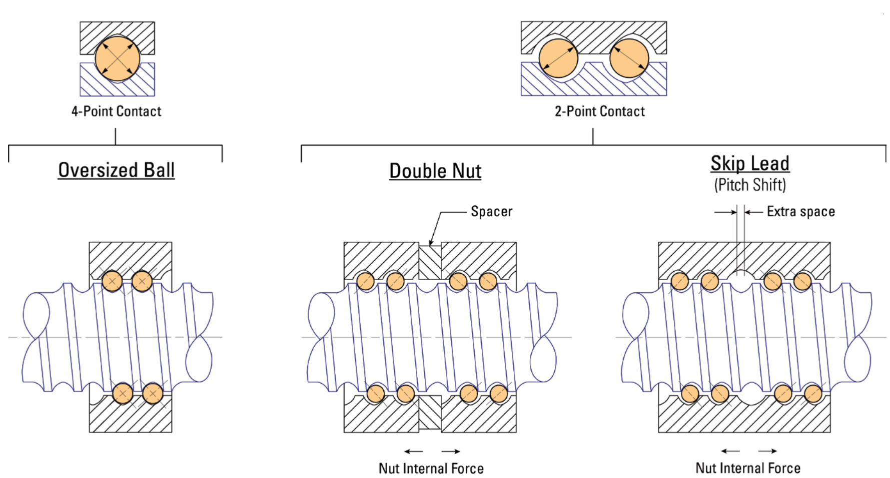


*Figure 4: Three main preload types with 2-Point Contact and 4-Point Contact.*

Whether the screw is whirled or ground

also impacts repeatability. As illustrated in Table 1, balls screws produced by rolling and with standard preloading can be specified for static loads of up to 400 kN, dynamic loads of up to 130 kN, lengths of 8 m and diameter up to 80 mm for precision classes up to P3. Larger and higher-precision class applications will typically require whirled or ground shafts.

| | Rolled | Whirled/Ground |
|---|---|---|
| Static Load | Up to 400 kN | Up to 6000 kN |
| Dynamic Load | Up to 130 kN | Up to 1500 kN |
| Length | Up to 8 m in one piece | Up to 16 m in one piece |
| Precision Class | Up to P3 | Up to P3/P1 |
| Preload Level | Standard | Up to 30% |
| Diameter | Up to 80 mm | Up to 160 mm |

*Table 1. Load handling capabilities by ball screw production type.*

Geometric orientation is another key mounting factor. With a horizontal orientation, the load equals the payload weight multiplied by the frictional coefficient. With a vertical orientation, the load equals the weight. The positional requirements determine which grade of ball screw is suitable for the application.

**5. Assess mounting issues**

The amount of mounting flexibility can have a significant impact on the available ball screw options. The configuration of the end support and travel distance will dictate the load and speed limitations of the ball screw. Ball screws are mounted in either supported or fixed configurations. A supported end holds the ball screw at one focal point and does not resist bending moments. A supported end is generally easier to align and install than a fixed one, so installation costs are typically lower. A fixed end resists bending moment loads because it is typically based on two bearings spaced sufficiently so the ball screw remains perpendicular to the planes of the rotary bearings. The fixed offers great column strength and higher critical speed.

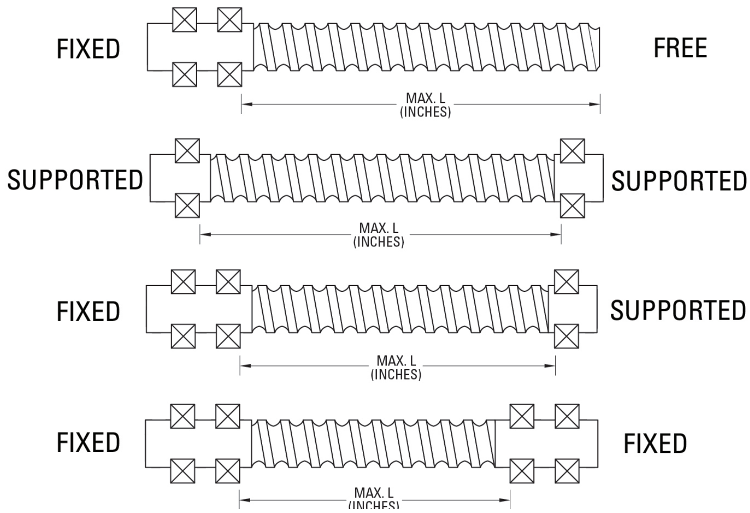


*Figure 5. End fixity factors.*

Figure 5 illustrates four fixity options. The assembly can be fixed at both ends, fixed at only one end and supported on the other, supported at both ends, or fixed at one end and free at the other.

The assembly should also be properly aligned with the drive system, bearing supports and load to achieve optimal performance and life.

**6. Determine whether you should be using the ball nut in tension or compression mode**

Tensile loads stretch the screw axially, which can elongate and potentially crack the screw. Compression loads put axial pressure on the screw and can make it bow out. A ball screw in tension can handle loads up to the rated capacity of the nut, so when using a ball nut in tension mode, simply check the rated capacity of the nut.

For a ball nut in compression, use the compression loading chart in Figure 6 to select a ball screw diameter that meets or exceeds the design load. All screws with curves that pass through or above and to the right of the plotted point are suitable for the example. The suitable compression loads shown in this graph are to not exceed the maximum static load capacity as given in the rating table for the individual ball nut assembly. For example: at a length of 85 in. (2159 mm), a system load of 30,000 lb. (133.5 kN) and with an end fixity of one end fixed and the other end supported - the minimum selection is a 1.750 x 0.20 inch ball screw assembly.

Either calculate the permissible compression loading of the nut or consult a compression loading chart supplied by the manufacturer to select the ball screw diameter that meets or exceeds your required load.

Ball screws work best with axial loads only. The screw must carry an axial load that is equal and opposite to the load generated on the ball nut by the motor's torque. The ability of ball screws to avoid buckling under a compressive load is called column strength, which is characterized by the ratio of the length to the diameter, making compression load dependent upon column strength. A ball screw with both ends fixed can be one and a half times longer than a ball screw with both ends merely supported and two and a half times as long as a ball screw with a free end while supporting the same amount of load without buckling. In general, column strength is the controlling design parameter because for long columns it is much lower than the material's strength in compression.

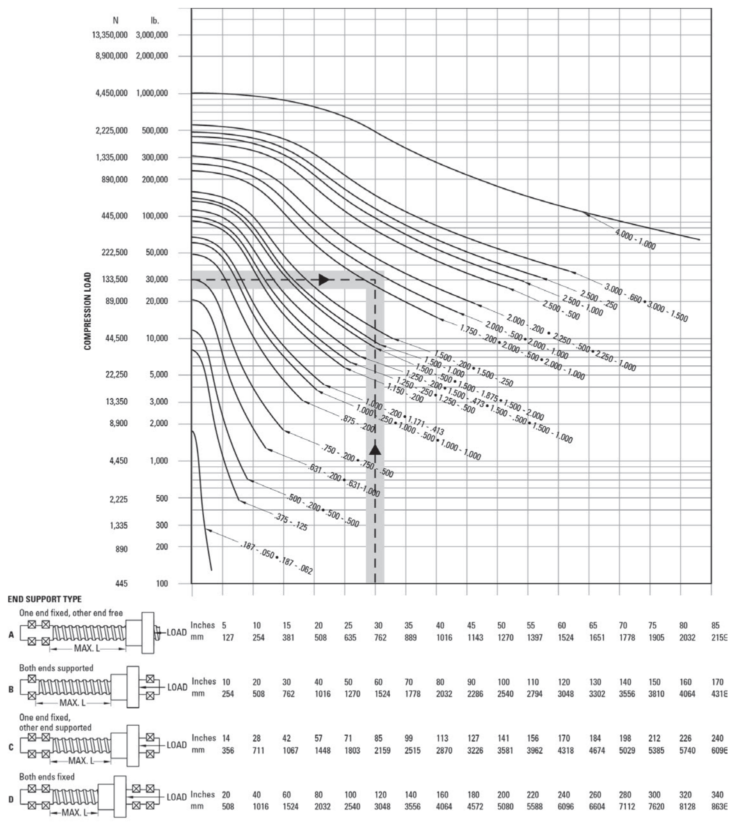


*Figure 6. Compression Load and Length Calculations.*

### 7. Consider vibration and harmonic challenges

The limiting speed of a ball screw is usually its tendency to vibrate based on its natural frequency. The critical speed is the rotary speed that sets up harmonic vibrations in the ball screw. Critical screw speed is dependent upon the screw's root diameter, unsupported length and the end support configuration. For example, a 100-in.-long, 1-in.-root-diameter ball screw with both ends fixed has a natural frequency of about 18 Hz. With both ends supported rather than fixed, the natural frequency of the same ball screw is reduced to about 8 Hz. If the rotational frequency of the screw matches the screw's natural frequency, slight imbalances in the screw can resonate. Excessive bending and bowing then keep the screw from working properly.

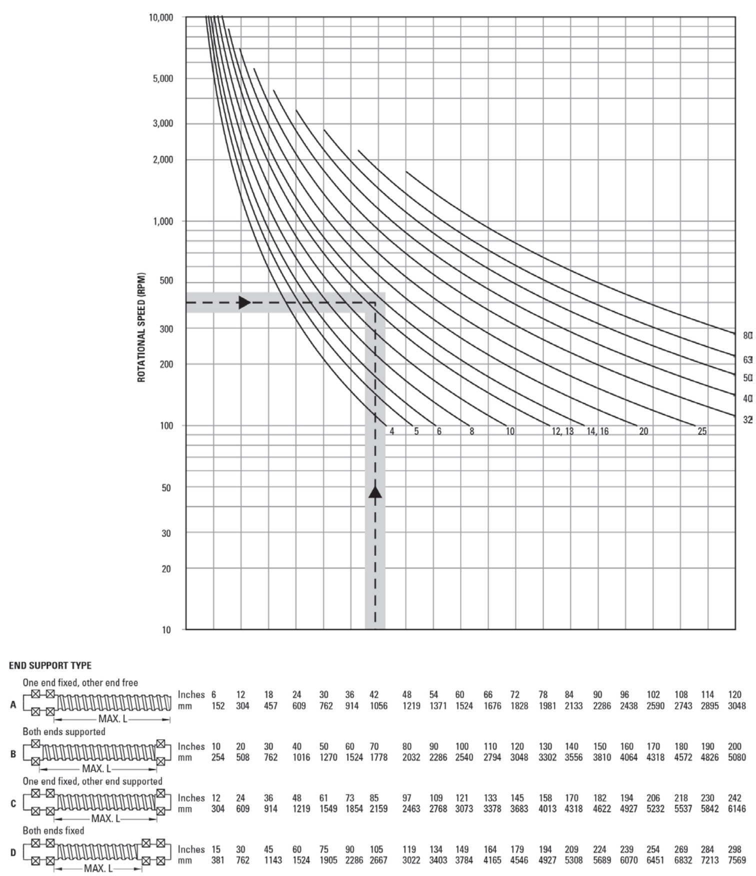


*Figure 7. Acceptable Speed vs. Length.*

Figure 7 shows the acceptable speed versus length for ball screws. All screws with curves that pass through or above and to the right of the plotted point are suitable for the example. The four end-fixity drawings on the bottom of the figure show the bearing configurations for supporting a rotating shaft, and the chart shows the effect of these conditions on critical shaft speed for the unsupported screw length. The acceptable velocities shown by this graph apply to the screw shaft selected and are not indicative of the velocities attainable of all of the associated ball nut assemblies.

If the load, life and speed calculations confirm that the selected ball screw assembly meets or exceeds the design requirements, then proceed to the next step. If not, larger diameter screws will increase the load capacity and increase the speed rating. Smaller leads will decrease the linear speed (assuming constant input motor speed), increase the motor speed (assuming constant linear speed), and decrease the input torque required. Higher leads will increase the linear speed, assuming constant input motor speed; decrease the input motor speed, assuming constant linear speed; and increase the input torque required.

Calculate the lead of the ball screw that will produce the speed requirement based on the following formula:

$$\text{Lead (in.)} = \frac{\text{Travel Rate (in./min.)}}{\text{rpm}}$$

Remember that every ball screw has its own rotation speed limit—the point of excessive vibration/ harmonics in the screw. This critical speed is dependent upon the end support configuration. (Figure 5) Be sure to use the manufacturer's acceptable speed chart to help determine the critical speed of a particular ball screw system.

**8. Explore other design possibilities**

Other factors to consider in ball screw selection are the ball return systems, applications interface, environmental resilience and imperial vs. metric measurement scale.

Ball return system choices impact cost, installation, noise and other application-specific factors depending upon the application. Common return types include:

- *External return tubes*, which are typically used in inch screws, are cost effective and easy to install, maintain and repair.
- *Internal button return systems*, which are typically used on low lead screws, are compact with no external radial protrusions to complicate mounting, and offer less noise and vibration than external returns.
- *Internal button return systems*, which are often used in 4-point contact, single nut and preload assemblies.
- *Internal end cap returns*, which are typically used on high lead screws, are compact with no external radial protrusions to complicate mounting. Their noise and vibration are also low compared to external returns.

In a typical application interface, a ball nut flange attaches the ball nut to the load. Threaded and cylindrical ball nuts provide a common alternative, but many other options exist. Bearing supports and custom end machining are available for most configurations to achieve application interface requirements.

Environmental resilience is another factor that could impact ball screw selection. Some units provide standard wiper kits that protect the assembly from contaminants and contain lubrication. Many options are available for materials and coatings that withstand different environmental conditions.

The choice of inch or metric scale may be dictated by the application, so making this choice too early in the process could restrict your options considerably. If you start with a commitment to inch scale, for example, you won't be able to address a need for high precision because inch scale is available only for transport-grade applications. But because it is possible to use a high-precision metric scale ball screw in an application that requires only transport-grade accuracy, you might find yourself weighing the pros and cons of each. If those are your options, the inch-grade ball screw could be the better choice because it can use external ball return systems to recirculate the ball bearings. Although external return systems tend to be noisier, less smooth and consume more space than internal recirculation systems, they are less expensive to manufacture and can use more ball bearings, which increases their load-bearing capacity or life expectancy, depending on the application or user preference.

**9. Understand handling and maintenance requirements**

Ball screws must be handled carefully prior to proper installation. Shocks to the ball bearings can damage the bearing races through brinelling or cracking. High loads or flexing of the screw can lead to bending. Keep the assembly packaged and lubricated and stored in a clean, dry area because debris and contamination can jam recirculation tracks, and high humidity or rain can cause corrosion.

Proper lubrication is vital to ball screw performance and life. Lubricants maintain the low friction advantage of ball screw assemblies over other motion control technologies by minimizing the rolling resistance between balls and grooves, and sliding friction between adjacent balls. Lubricants are often taken for granted but the right choice for each application ensures a ball screw that will perform properly for its calculated life.

Oil can be applied at a controlled flow rate directly to the point of need, and it will clean out contaminants as it runs through the ball nut. It can also provide cooling. On the other hand, a pump and metering system is needed to apply oil properly, as oil also has the potential of contaminating process fluids.

Grease is less expensive and requires less frequent application than oil, and it does not contaminate process fluids. On the other hand, grease is hard to keep inside the ball nut and tends to build up at the ends of ball nut travel, where chips and abrasive particles can accumulate. Incompatibility of old grease with re-lubrication grease can also create problems, so checking compatibility carefully is critical. A load-carrying grease can help extend the life of an assembly, but the overall load rating will not change.

Noise is a related consideration for some applications. Larger ball screws utilize larger ball bearings and are therefore inherently noisier. External return systems are also inherently noisier than internal return systems. The use of spacer balls can reduce the noise of a ball nut but reduces the load capacity. The selection and proper application of grease can also reduce the overall noise level. Minimizing or even eliminating backlash can also reduce noise in an assembly.

Maintenance teams should inspect ball screws periodically to avoid downtime and maximize life. Performing the following checks will help you spot indicators of trouble:

Check for metal fragments that may cause damage and could be an indication of broken balls or component wear.

- Measure lash to verify component wear.
- Check the races for wear, spalling, brinelling and contamination.
- Check to make sure the screw is lubricated and free of contamination and corrosion.
- Check that all connections are tight and that there are no vibration issues.
- Check the drive system to make sure that the drive torque is constant, and the ball screw is operating smoothly and quietly.
- Noise levels should be the same as on the first day of operation. The ball nut travel should be smooth and regular. Any change in noise level or "feel" is an indication of internal damage.

**10. Take full advantage of online sizing and selection tools**

Web-based sizing and selection tools represent an increasingly popular approach to simplifying the machine design process. Such resources can significantly reduce the time required to identify optimum standard components that meet the vast majority of application requirements. A popular example is the Ball Screw Selector Tool (www.thomsonlinear.com/en/products/ball-screws-products) from Thomson Industries. Using an intuitive layout and visual selection process, the ball screw search is narrowed immediately for users. Real-time adjustments are reflected per defined filter parameters, and results include up-front lead times and pricing, links to 3D models, catalog links and product details, and the option to purchase instantly.

## Conclusion

Ball screws provide an excellent method for translating rotational motion to linear motion for many applications, including those where high loads and close tolerances are involved. To apply the correct type of ball screw in a particular application, the design engineer must consider the advantages and capabilities of each. Selecting the right technology can reduce design complexity, improve performance and reduce the overall cost of the assembly.

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