

# Choice and calculation of ball screw for linear actuator

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**Abstract:** The selection of an appropriate ball screw for a linear actuator is a critical factor in ensuring precision, efficiency, and durability in automated systems. This paper presents a systematic approach to selecting a ball screw based on key operational requirements, including axial load, travel distance, linear speed, acceleration time, accuracy, backlash tolerance, and service life expectancy. By analyzing and calculating the technical specifications, we determine optimal parameters for high-performance linear actuation.

**Keywords:** BALL SCREW, LINEAR ACTUATOR, LEAD SELECTION, AXIAL LOAD

## 1. Introduction

The selection of a ball screw is a multi-step process that involves careful calculation and assessment of various parameters. In order to determine the appropriate lead and diameter of a ball screw, some essential marks have to be taken into account. Adjustments to selected ball screw parameters may be necessary to ensure optimal performance. According to [3] there is no single formula for selecting a ball screw, rather it is a structured procedure with interdependent steps that are needed to be followed. Although online tools provided by manufacturers can assist in the selection process [14], it is recommended [11] to manually go through the calculation to ensure the right measurements will be the input in the design process.

Ball screws appear in many machines and devices that require accurate and efficient linear motion. They are commonly used in machine tools (e.g. CNC milling machines and lathes) to position tables [9] and tool carriages, in robotics and automated assembly equipment [7] for precise actuator movement, and in aerospace applications (such as aircraft control surface actuators and missile fin controls) [4].

For example, modern CNC machines use ball screws on each axis to achieve high positioning accuracy and repeatability [6]. In the automotive field, ball screws are found in power steering systems, where an electric motor's rotation is converted to linear motion to steer the wheels [1]. High-precision ball screws are also used in semiconductor manufacturing equipment (steppers) and medical devices, where very fine positional control is required [8].

## 2. Material and manufacturing properties of the ball screw

A fundamental aspect of ball screw selection is choosing between ground and rolled ball screws.

Ground ball screws and rolled ball screws differ primarily in their manufacturing process. Rolled ball screws (see Fig.1) are manufactured by pushing a stock bar through rotating tools and dies in a single operation, a cold deformation process that allows mass production. Due to their manufacturing process, rolled ball screws are more cost-effective but exhibit lower accuracy.

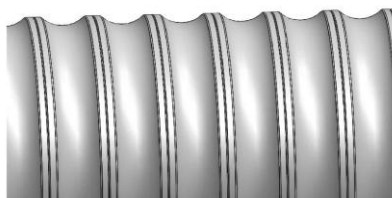


Fig. 1 Rolled screw threads [10]

Ground ball screws (see Fig. 2) are manufactured using an abrasion process, which is not easily automated, thus making mass production impractical. However, this process results in high precision and minimal backlash, at a higher cost.



Fig. 2 Ground screw threads[13]

Most ball screw shafts and nuts are made from high-strength alloy steels that are case-hardened or through-hardened to withstand the contact stress of the balls. A typical material is chromium-molybdenum alloy steel or a bearing steel (e.g., ASTM 52100 chrome steel) which offers a hard surface for wear resistance and a tough core. The balls themselves are usually hardened steel (often the same 52100 bearing steel).

### Backlash and accuracy grade

Backlash is defined as the axial and angular clearance between the nut thread and the screw, backlash is a fixed deviation in travel throughout the length of the screw. It can be eliminated through preloading, which applies a fixed load on the nut to prevent axial movement. If a ball screw assembly has backlash, the nut can move a tiny amount without corresponding rotation of the screw (or vice versa), which can cause positioning errors and a "loose" feel in the mechanism. Backlash is measured in micrometers or thousandths of an inch of axial play. A ball nut with all lash removed (zero clearance between balls and grooves) is referred to as preloaded, meaning it has an intentional internal load to eliminate any free play.

The effects of backlash in precision applications, backlash is undesirable because it causes inaccuracies whenever motion changes direction (for instance, in CNC machining, a loose screw could cause overshoot or stop, requiring compensation in control software). However, backlash does *not* affect the lead accuracy per se – even a high-grade screw can exhibit backlash if the nut isn't preloaded. Backlash mainly affects repeatability and bidirectional accuracy, not the cumulative error over length (which is grade-related). Many high-end ball screws are sold as "zero-backlash" which indicates they have internal preload.

Ball screw accuracy is categorized into various grades ranging from C0 to C10 [12]. As the grade number decreases, the precision increases. The grades C0 to C5 represent precision ground ball screws, while C5 and above represent rolled ball screws. Accuracy grade represents the ball screw lead error. At each revolution of the nut, a small lead error accumulates, affecting overall precision.

Manufacturers typically define this error per 300 mm of travel. For example, if a ball screw has a lead of 5 mm, the net travel per revolution should be exactly 5 mm, but in practice, minor errors exist.

## Lead and pitch

The pitch of a screw (see Fig. 3) is the distance between adjacent threads, measured parallel to the screw's axis. The lead is the linear distance the nut travels per one revolution of the screw. For a single-start thread (only one thread running along the shaft), the lead is equal to the pitch. For a multi-start thread (multiple thread forms intertwined on the same screw), the lead is the pitch multiplied by the number of thread starts [12].

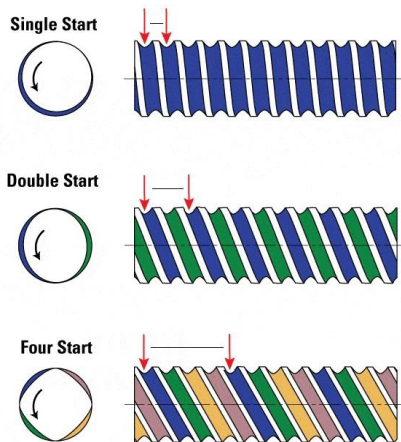


Fig. 3 Lead and pitch in the single and multi-start screw [12]

## 3. Methodical approach and formula calculations

### Calculation of lead

For example, a screw with a 5 mm pitch and two starts will have a 10 mm lead (meaning the nut moves 10 mm per revolution). The formula is:

$$\text{Lead} = \text{Pitch} \times \text{Number of Starts} \quad (1)$$

Most ball screws are single-start, but multi-start ball screws exist for applications needing a very high lead. It's important not to confuse these terms: pitch is a geometric property of the thread, while lead is a functional outcome (travel per revolution) – on a single-start screw they coincide, on a multi-start screw the lead is larger than the pitch.

**Calculation of an appropriate speed:** The lead of the ball screw is crucial in motion control because it influences the system's speed, resolution, and mechanical advantage. A larger lead means the nut will translate a longer distance for each rotation of the screw, resulting in higher linear speed capability. For a given rotational speed (in RPM), linear speed is calculated as:

$$V_{\text{linear}} = \text{Lead} \times \text{RPM} \quad (2)$$

Thus, if you need a fast-moving linear actuator, a larger lead can achieve that speed with a moderate screw RPM. However, a higher lead (steeper thread) also requires more torque to generate the same thrust force, as it's akin to a steeper incline. In fact, when comparing two screws, a screw with a higher lead will demand more driving torque to produce a given linear force (and conversely, a smaller lead provides a mechanical advantage, requiring less torque) [12].

Another consideration is resolution: a smaller lead allows finer incremental movement for a given motor step or encoder count (higher resolution), whereas a large lead might make it difficult to achieve very small position increments. As a rule of thumb, a numerically small lead provides higher positioning resolution and greater force multiplication (at the cost of speed), while a large lead favors speed but trades off some force and resolution.

## Calculating Buckling load

When a ball screw is under compressive axial load (common in vertical axes or if the screw is pushing a load), (see fig 4), it acts like a column under compression.

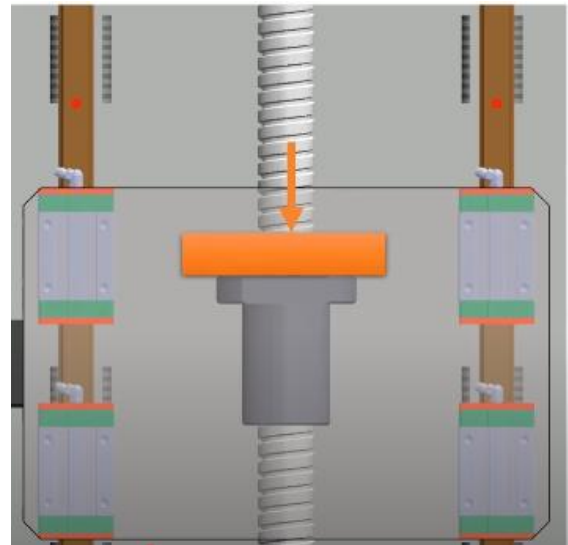


Fig. 4 Screw under axial load [12]

Long, slender columns can fail by buckling at relatively low loads, well before the material's yield strength is reached. Therefore, even if the static load rating of the ball screw (based on material strength) is high, a long screw might still buckle under a lower load. The buckling load  $F_{\text{buckling}}$  for a column is given by Euler's formula:

$$F_{\text{buckling}} = \pi^2 EI / L^2 \quad (3)$$

where  $E$  is Young's modulus measured in GPa,  $I$  is the area moment of inertia of the screw cross-section ( $\text{m}^4$ ),  $L$  is the unsupported length (m). Rather than computing this from scratch, designers use charts or manufacturer calculations.

### The choice of a ball screw for a linear actuator in this study is influenced by several performance parameters:

- Axial Load (50 kg): The screw must support and transmit force without excessive deformation.
- Travel Distance (1000 mm): The ball screw should accommodate the required stroke length.
- Linear Speed (0.4 m/s): The lead of the ball screw should be chosen based on speed requirements.
- Acceleration Time (0.2 sec): A high Dm-N rating is required to sustain rapid acceleration.
- Linear Accuracy (0.5 mm within 1000 mm): Precision classification should meet the positioning accuracy requirement.
- Acceptable Backlash (0.1 mm): A preloaded nut assembly must be selected.
- Expected Service Life (20,000 hrs): Load capacity calculations must ensure sufficient fatigue resistance.

## 4. Analysis of ball screw specifications

Using the HIWIN Ball Screw Catalogue [12], an analysis of the selection methodology will be conducted and the appropriate specifications to meet the given operational requirements will be derived.

### 4.1. Load and stiffness considerations

The dynamic load capacity ( $C$ ) must be at least five times the applied axial load. For an axial load of 50 kg, a minimum  $C = 250$  kg is required. To maintain stiffness and eliminate backlash, a preloaded double-nut (DF) configuration is recommended. Additionally, angular contact ball bearings (60-degree contact angle) are necessary to enhance axial rigidity.

### 4.2. Lead selection and speed calculation

From formula (1) The lead ( $L$ ) is determined using the relationship: where is the linear speed and is the maximum rotational speed. Given a typical servo motor speed of 3000 RPM, a lead of 10-20 mm is suitable to achieve the required 0.4 m/s speed. The ball screw diameter must be chosen to meet critical speed constraints ( $Dm-N$  rating  $\geq 100,000$ ) to prevent buckling and vibration.

### 4.3. Critical Speed

When determining the lead, it was necessary to start from the motion requirements of the model. We need to calculate the required linear speed (stroke length per unit time) and the available motor speed. From which we can derive a suitable lead (Lead = required linear speed / motor RPM). It is necessary to ensure the chosen combination is feasible because extremely high leads might yield impractically low motor torque or may exceed the screw's critical speed. In other words it would be better to pick a lead that meets the speed requirements but also consider the torque and resolution implications. Many designers choose a moderate lead and then gear the motor appropriately if needed, rather than pushing to an extreme [10]. It's also worth noting that ball screws maintain high efficiency (~90% or more) across different leads [2], so unlike other screws, this model will not lose much efficiency with a smaller or larger lead; the choice is more about performance trade-offs (speed vs precision) than efficiency.

### 4.4. Accuracy and backlash control

Control For a linear accuracy of 0.5 mm over 1000 mm, a C5-grade precision ground ball screw (lead accuracy  $\leq 18\mu\text{m}$  per 300mm) is recommended. The backlash requirement of  $\leq 0.1$  mm (100  $\mu\text{m}$ ) is met using a preloaded DF nut configuration, which ensures near-zero axial play.

### 4.5. Buckling load

**Calculation process:** For example, a manufacturer might provide a graph of "Allowable axial compressive load vs. screw length for each diameter"—the designer should ensure the application's maximum compressive force is below the curve for the chosen diameter (with a safety factor) [5].

In the earlier design stage, an initial diameter would have been chosen partly to handle expected loads; the buckling check formalizes that by considering the actual mounting and length. The maximum compressive load the screw will face is identified (this could be the force needed to lift the load, plus any extra from dynamics). Using the screw length and support type, the critical buckling load is derived. Many designers apply a safety factor (e.g., factor of 2) to the Euler result for added insurance, given uncertainties in load and imperfections in the screw. If the available buckling load is below the required range, choose a larger diameter or change support conditions. For instance, switching from a free end to a supported end can significantly raise the buckling capacity (as the effective length is halved or better)

### 4.6. Service life expectancy calculation

The expected lifespan of a ball screw is estimated using:

For an axial load  $F = 50$  kg and dynamic capacity  $C = 250$  kg, the ball screw is projected to exceed 20,000 operational hours, satisfying the longevity criterion.

Ball screws, like rolling element bearings, are subject to material fatigue over time due to the cyclic stresses between the balls and the raceways. The expected life of a ball screw is usually defined in terms of  $L_{10}$  life ( $L_n$  the number of revolutions or hours at which 90% of identical screws will survive before surface fatigue begins). The life is a function of the applied load relative to the dynamic load rating  $C$ . For ball screws, a life equation analogous to bearing life is used:

$$L_{10} = (C/P)^3 \times N_{rev} \quad (4)$$

Where  $P$  is the equivalent mean load on the screw and  $N_{re}$  is a baseline number of revolutions (typically one million for the definition of  $C$ ). Often this is expressed in terms of hours of operation ( $L_h$ ):

$$L_h = 10^6 / 60N \quad (5)$$

which gives the life in hours for a constant speed  $N$  (rpm) and constant load  $P$ . More generally, for variable loads and speeds, we should compute a weighted or mean load (using the duty cycle) and a mean speed, then apply the formula. Manufacturers sometimes provide software or to estimate life for different load scenarios.

**Verification process:** We define the desired life for the application. Industrial machines often target on the order of tens of thousands of hours. In the example of the study, machine tool ball screws will be designed for ~20,000 hours of operation. Using the selected screw's dynamic capacity  $C$  (from the catalog [12]) and the application's load profile, calculate the  $L_{10}$  life. If the calculated life is lower than desired, the selection may need to be revised – usually by choosing a screw with a higher dynamic capacity (which often means a larger diameter, or a different ball nut design with more circuits or larger balls). Reducing the operating load or speed (duty cycle) can also increase life, but again the load is typically dictated by the application's needs. It's worth noting that running at lower loads than the screw's capacity dramatically increases life (due to the cubic relationship). For instance, if the operating load is only 50% of  $C$ , the life in rotations is roughly  $(1/0.5)^3 = 8$  times the baseline (eight million rev instead of one million for  $L_{10}$ ). Conversely, pushing a ball screw near its dynamic rating will result in a short life. Therefore, part of selection is choosing a screw size where  $P/C$  is low enough to give the desired reliability.

If all three verification checks (critical speed, buckling, life) are satisfactory, then the chosen ball screw can be considered suitable.

## 4. Recommended ball screw specifications

Based on the analysis of the initial performance parameters, calculations and reference the following specifications are recommended:

**Table 1.** Recommended ball screw specifications

Parameter	Recommended Specification
Lead (Pitch per Revolution)	10 - 20 mm
Screw Diameter	20-32 mm
Preload Method	Preloaded Double Nut (DF) Type
Accuracy Grade	C5 (Lead Accuracy $\leq 18\mu\text{m}$ per 300mm)
Backlash	$\leq 0.1$ mm (100 $\mu\text{m}$ )
Lubrication	G01 Heavy Load Grease
Service Life Expectancy	$\geq 20,000$ hrs

## 5. Conclusion

The selection of a ball screw is a careful engineering process that integrates application requirements with manufacturer specifications and engineering principles. By calculating the needed lead and choosing a suitable diameter, specifying an accuracy grade that meets positional tolerances, and verifying the selection against critical speed, buckling, and life criteria, we have arrived at an optimal ball screw choice. The academic approach to ball screw selection emphasizes traceable reasoning and adherence to standards: every choice (for example, using a C7 rolled screw of 20 mm diameter and 10 mm lead for a given actuator) can be justified by calculations and references to catalog data or standards. By following a structured procedure and considering the factors outlined, engineers can ensure the chosen ball screw will deliver the required motion precision, load capacity, and durability in service.

This ultimately leads to a reliable and efficient mechanical system, whether it be a high-precision machine tool or a general industrial actuator.

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