Six keys to achieving better precision in linear motion control applications

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Optimize precision by focusing on drive and mechanical factors that affect control engineering performance

Equipped with even the most sophisticated motion controller, machine designers may find it difficult to achieve exact linear motion precision unless their mechanical components are accurately specified for the application. That’s why understanding the parameters for the given application, and the market, is the first step in attaining

Achieving precise linear motion...

Consider these factors when specifying linear motion systems:

1. **Travel accuracy**—minimizing system pitch, yaw or roll depends on the quality of the travel guidance system and the surface to which it is mounted. Factors in the bearing circulation can also cause precision-reducing vibration.

2. **Positioning accuracy**—depends on tolerances of the drive element. For ball screws, there can be significant lead-error or lead-deviation within the ball screw or ball nut. The degree of error often depends on the method used to create the screw threads.

3. **System/machine frame stiffness**—an unstable frame often reduces the efficiency of the finest control system.

4. **Operational speed**—critical speed and characteristic speed should be addressed to reduce vibration and other influencing factors.

5. **Thermal considerations**—all linear motion components will generate heat that must be taken into account.

6. **Machine resonance**—nearby machines or even forklifts can be a source of vibration.
the required degree of precision. Different markets have varying definitions of precision, from the nanoscale level in the semiconductor industry to the relatively generous 0.01” standards seen in packaging or newspaper printing. That usually determines the precision “target” you set. It’s also important to know the operating environment involved in each application, because some environments are more challenging than others for hitting that target.

Let’s start by considering how precision is defined. Precision is a combination of accuracy, positioning and repeatability. Accuracy, the discrepancy between a movement’s target position and the actual achieved position, reflects motion targets being approached from different directions (multi-directional). Positioning accuracy is the maximum deviation between the actual and target positions during each motion. Repeatability relates to how precisely a linear motion system positions itself when repeatedly approaching a position from the same direction, taking into account fluctuations in the deviation of the actual position from the target position. In any application, you will find it is easier to achieve improved results in all of these accuracy parameters by focusing on the following six areas.

1. Travel accuracy
Travel accuracy measures pitching (up and down), yawing (side to side) or rolling (around the axis) (see Figure 1). Minimizing these motions depends on the quality of the travel guidance system and the surface it is mounted to. Linear motion systems typically conform to the surface on which they are mounted, so travel accuracy varies with machine surface alignment, preparation and tolerances.

High-quality travel guidance systems follow industry standard tolerances for height, width and parallelism. For example, Bosch Rexroth offers a range of six accuracies, from N (Normal Precision) height/width tolerances of ±100 microns/±40 microns to UP (Ultra Precision) height/width tolerances of ±5 microns.

Keep in mind, as the tolerance bandwidth decreases, the costs of the components increase. Spending more on the components and not addressing the structural elements as mentioned for flatness and straightness will diminish the output travel accuracy for the axis and machine.

The circulation of anti-friction elements (bearings) can cause precision-reducing vibration as they transition from “load-bearing” to “non-load bearing” in the runner block. This re-circulation can be optimized to provide extremely smooth motion as the balls circulate in the bearing raceways.

2. Positioning accuracy
Positioning accuracy depends on the tolerances of a drive element, such as an electromechanical ball screw, hydraulic or pneumatic cylinder, electric linear motor or rack and pinion, among others.

Ball screws can have significant lead-error or lead-deviation within the ball screw or ball nut—the element typically connected to, and driving, the load. The degree of error often depends on the manufacturing method used to create the screw threads. Grinding processes can
introduce lead-error from the inherent machine inaccuracies, tool wear, or heating of the ball screw shaft during the grinding process. Forming threads via the rolling process can introduce lead-error primarily through the post-process heat treatment. Grinding has traditionally been recognized as more accurate than rolling, but the gap is narrowing. Some Rexroth precision-rolled screws can deliver Class 5 or even Class 3 precision for travel (lead) deviation, for a maximum deviation of ±12 microns across 300mm of travel. You can achieve further accuracy gains using electronic correction processes, which can compensate for small lead-errors across standard travel runs. **Figure 3** shows a corrected lead deviation of up to 13 microns across 700 mm of travel.

Adding external feedback to the machine axis can also maximize positional accuracy. This can be done indirectly using a rotary encoder, or directly using a linear scale. For example, Bosch Rexroth’s IMS (Integrated Measuring System) integrates a scale into the guide rail and a sensor head on the bearing block. Positional feedback from the sensor communicates directly to the servo drive to correct the final motion position.

### 3. System stiffness

This is an area where mechanical factors often reduce the efficiency of the finest control systems. The machine’s frame/base rigidity and thickness, construction material (e.g., aluminum vs. steel) and frame construction (solid or tubular) can all have an impact on precision. Motion component-based factors such as preload, axis length, types of anti-friction elements and bearing support, as well as the fasteners connecting the linear motion system to the frame can all indirectly influence the output precision of the machine.

System stiffness is critical because any force or load applied to the motion components—downward, upward or sideways—can cause system deflection, an enemy of repeatability. The greater the force, the more deflection will be experienced. To combat this, designers often improve the overall rigidity or stiffness of the linear guide block by introducing preload in the form of oversized anti-friction elements. **Figure 4** shows a typical preload, using oversized rolling elements (Dk) in the guide rail gap (diameter D). Linear guide manufacturers typically offer widely varying levels of preload to minimize the amount of deflection experienced.

The drive element can contribute to total system rigidity through the stiffness of its support bearings, ball nut unit, and the ball screw itself. The
biggest factor impacting the stiffness of the screw drive is its length: the longer the screw, the harder it is to compensate for deflection. Compensation techniques include extra preload or selecting a stiffer ball nut.

4. Speed
Demanding high-throughput applications can offer tough challenges because short cycle times sometimes have speed requirements that push the limits of linear guide and ball screw speed/acceleration capabilities.

The first limit is the ball screw shaft’s critical speed—the speed at which the screw will vibrate or oscillate excessively (known as screw whip). This speed depends largely on the shaft length plus bearing support choices. The ability of designers to alter critical speed is limited mainly to their choice of end-bearing support systems. Fixed-fixed mountings allow the highest critical speeds, and fixed-free systems, the lowest. With a fixed mounting, the bearing arrangement is truly fixed on the screw and has a bearing set that is designed to support axial loading. Floating mountings may be chosen because they introduce less friction to the system, allowing better thermal performance, but they have a lower critical speed than fixed mountings. Floating mountings are typically just a radial bearing to support the radial load or weight of the screw out in space. This arrangement gets its floating name as the bearing is allowed to float or move in the pillow block housing as the screw spindle expands and contracts due to thermal changes.

The second limitation is the bearing system’s characteristic speed, based on the circulation of anti-friction elements through the system. In the case of the ball screw, this is the ball nut that represents the bearing system. Temperature, vibration, and inertia of the balls all play a role. The characteristic speed is often called the Dn Factor, calculated by:

\[ d_0 \times n \leq \text{Dn Factor} \]

\( d_0 \) = ball screw nominal diameter (mm);
\( n \) = speed in rpm.

The lower of the two speed values is most critical for precision in motion control. Characteristic speed is independent of shaft length, but critical speed declines with increasing length. Once critical speed is reached, vibration increases, accuracy drops and machining surface finish quality will diminish (in a machine tool, for example). In addition, the ball screw assembly will fatigue much faster.

5. Thermal considerations
All linear motion components (motor, bearings, nut) will generate heat that must be accounted for; proper management of these thermal influences can help improve the performance and the precision of a system. Different parts of an axis can have different temperatures based on running time, dynamic cycle and process force on each part. Allowing bearings to float within a pillow block can allow for the expansion and contraction behavior with a ball screw assembly, but a trade-off is that they are less rigid. Using a combination of fixed bearings or bearings capable of supporting axial/thrust loads and floating pillow blocks with radial bearings allow for this thermal flexibility, while optimizing speed characteristics.

Thermoelastic deformation presents another challenge for engineers, as heat influences linear expansion of all components. Deformation could cause misalignment or displacement, which puts excess force on the bearings and nuts. This force creates friction, which leads to even more heat generation. The higher the rigidity that an application requires, the more this friction-generated heat will impact alignment, stiffness and performance. The good news is that with the advancement of drive and control electronics, designers can offset or compensate for these thermal influences.

6. Machine resonance
All of the above factors can cause machine resonance or vibration, which compromises precision and quality of surface finish (for example, on a machined work piece). In extreme cases, vibration (such as that produced by exceeding critical speed) can cause “whipping” of the screw, and machine damage. Other possible causes of vibration include:
- Excessive run-out or improper concentric rotational screw behavior in relation to the center axis of the ball screw spindle, drive journal, etc.
- Excessive system or component backlash
- External influences (resonance from nearby machines, forklifts, HVAC system, etc.). This is often overlooked, and can be counteracted by placing the machine on a special, isolated foundation pad.
Putting it all together: Design decision-making

Optimizing for precision in any target market, for any particular application, requires a long-range view of the market. In some markets, greater precision may not justify expending substantial resources for minor improvements—but then again, it may help differentiate a new product. You should also keep in mind the specific definition of precision called for by the standards and necessities of the market.

In a particular application, extremely high throughput requirements may also limit the precision that can be achieved. The need for quick changeover times may require some trade-offs in precision to attain a simpler design.

Finally, consider emerging market requirements, particularly in the area of energy consumption and lean manufacturing. Improved precision may produce a significant yield in reduced waste and rejected parts, adding yet another element to the known benefits of more precise linear motion systems.

For any machine design challenge, it’s important to recognize that the best results are achieved when engineers account for the critical role of mechanical factors and machine structure. These are necessary steps toward attaining maximum precision.