MOTION DESIGN GUIDE

LINEAR BEARINGS

ROUND SHAFT • LINEAR BUSHINGS

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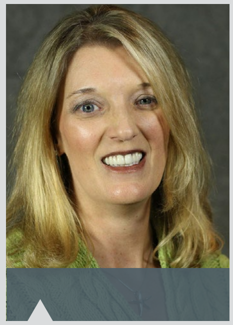
Linear bushings are a type of linear bearing based on round or modified round shaft upon which an engineered cylindrical bushing (studded on its inner diameter with rollers) rides. A related technology — that of ball splines — are a type of linear bearing based on round shaft *having precision-machined grooves down its axial length*. Riding upon this is a sleeve-shaped cylindrical nut with geometry compatible with the shaft's geometry.

In this Design Guide, the editors of Design World detail the most common linear bushing and ball spline types for motion control — as well best practices for sizing, selection, and installation.



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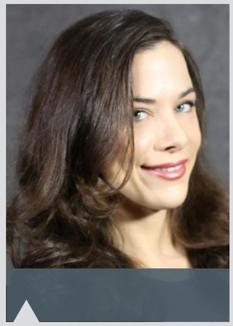

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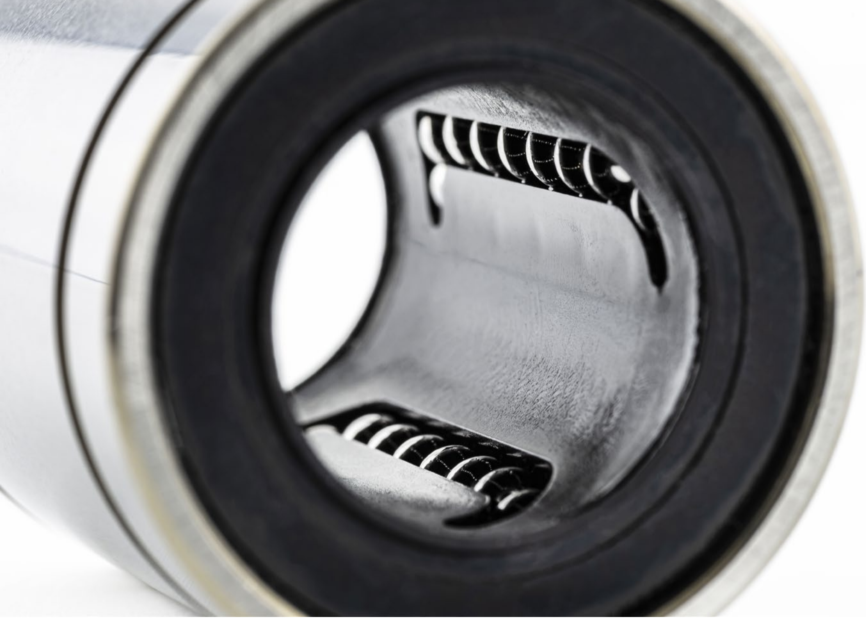


DEEPER DIVE ON THE DIFFERENCES BETWEEN **LINEAR BUSHINGS AND BALL SPLINES**

Shown here is a linear bushing inner diameter (ID) with its ball bearing elements clearly protruding. These balls are what make contact with the linear shaft of this linear-bearing option.

Linear bushings (sometimes called ball bushings) are a type of linear bearing that includes two basic components:

- A hardened shaft having a round or modified circular cross section
- A sleeve-shaped cylindrical nut (usually called a bushing) having captive circuits of recirculating balls.

The bushing (via its ball-bearing elements) rides along this hardened shaft (usually made of specially engineered steel) to provide low-friction linear guidance.

Linear bushings were first patented in 1940s and became commercially available in the 1950s. Until the profiled-rail linear guides came onto the motion-control scene in the 1970s, these linear bushings were the primary form of linear-motion bearing support for applications not requiring the high load capacities and accuracies delivered by machined linear ways. But make no mistake: As linear-bushing designs evolved over the decades, their increased load capacities and new self-aligning capabilities have meant they've endured as a top choice for linear guidance in motion applications.

Today linear-bushing shaft sizes range from the miniature (to just a couple millimeters in diameter) to 100 or more millimeters — allowing application in packaging, paper processing, assembly, and general-automation applications.

One caveat we'll explore in this Design Guide: Linear bushings provide widely applicable load-carrying capacities with very low friction but (despite their simple design and easy installation) do require precision sizing during specification. Myriad factors affect linear bushing life and failing to account for these parameters during sizing could make for a machine design that's undersized for the application or one that fails to deliver the expected travel life.

Now consider the other focus of this Design Guide — that of ball splines.

Ball splines are often lumped together with linear bushings — with some manufacturers even calling them *torque-resistant ball bushings*. But ball splines offer functionalities beyond those of traditional linear bushings. That's because ball splines integrate:

- An essentially round shaft *having precision-machined lobes or grooves down its axial length*
- A sleeve-shaped cylindrical nut having captive circuits of recirculating balls in protruding arrays that are compatible with the mating shaft's particular geometry.

> Standard ball splines provide linear motion and torque transmission. In contrast, rotary ball splines combine linear and rotary motion in one device.

Here, the nut is much like that of a ballscrew assembly, but (at least in most cases) with a screw having a 0° lead angle. The exception to this is rotary ball splines, which feature spiraling grooves down their shafts.

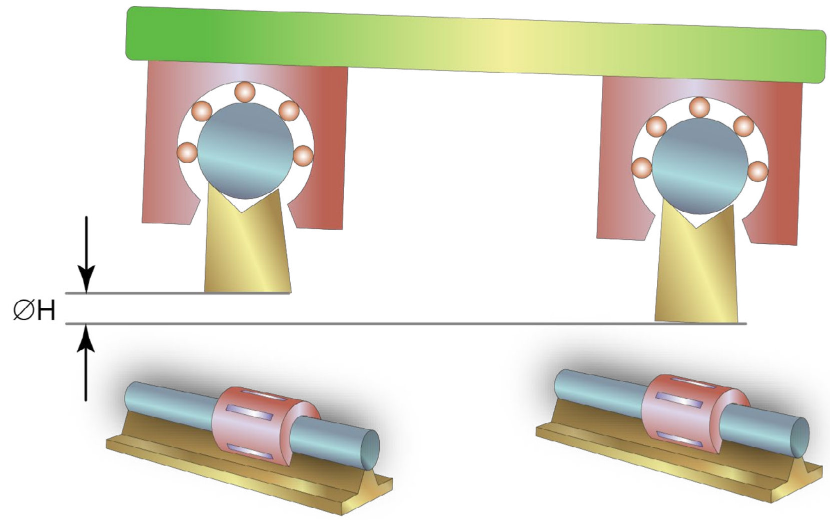
As we'll explore more fully in this Design Guide, ball-spline shafts can have two or more grooves running down their length — with the exact groove count depending on linear-bearing load capacity and shaft diameter. Just as their linear-bushing cousins, ball splines are also available in a wide array of diameters — to serve in machine-tool punching or riveting machines (often on their Z or Zθ axes) as well as grinding equipment, transfer machines, wire winders, indexing stations, and various machines' spindles.

MORE ON **LINEAR-BUSHING INSTALLATIONS** AND SELF-ALIGNING VARIATIONS

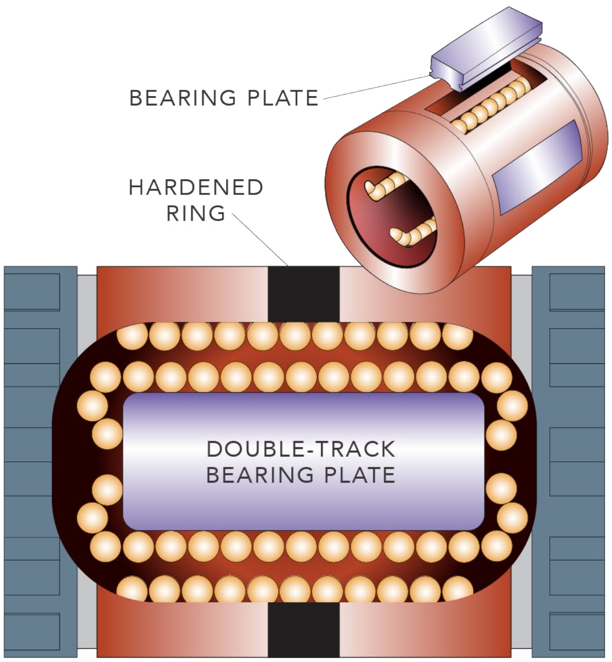
Linear-bushing assemblies consist of load-bearing plates, a ball retainer, the constrained steel balls, end caps or rings, and seals. External loads are transferred from the load plates (analogous to the outer race of a radial bearing) through the steel balls, and to the shaft (analogous to the inner race of a radial bearing). Traditional linear bushing designs produced point contact between the balls and the load plates. This point contact provided extremely low friction, but also limited the load capacity of the bushing.

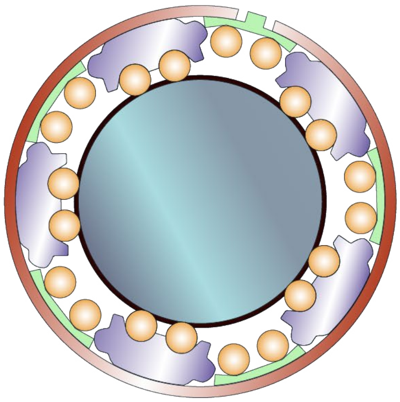
Although linear bushings are still available with this design, most current designs incorporate a groove in the load plate to provide better conformity with the load-carrying balls. The change from point contact to conformity increases the load capacity by three times that of a traditional design … which in turn increases dynamic bearing life 27-fold.

Despite the higher load capacities and stiffness of profiled rail guides, one of the benefits that linear bushings provide is their suitability for applications where high-precision machining of mounting surfaces and alignment of components is not feasible. For example, to support moment loads, linear guides (whether shafts or profiled rails) are often used in pairs. If the guides aren't perfectly aligned with respect to their height, profiled rail versions will bind, experience high friction, and have a greatly reduced life. Linear bushings, on the other hand, can rotate (roll) around the shaft, compensating for the shaft misalignment.



Linear bushings can rotate around the shaft to compensate for variance in shaft heights.





Grooved load plates allow conformity with the load-carrying balls, resulting in higher dynamic load capacity. A hardened ring around the outer bore serves as a pivot surface for the load plate. This allows alignment in roll, pitch, and yaw directions.

(continued)

MORE ON LINEAR-BUSHING INSTALLATIONS AND SELF-ALIGNING VARIATIONS

As a rule of thumb, 1 to 2 mm of height difference can be compensated when shafts are mounted 300 mm or more apart.

In addition to their inherent roll capability, linear bushings can also be self-aligning — meaning they can rotate in the pitch and yaw directions. That in turn lets them compensate for flatness or alignment errors or deflection in the shaft.

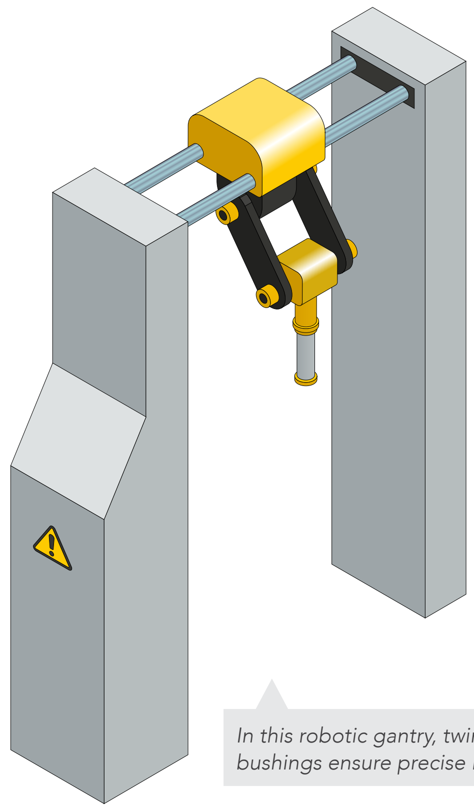
This self-alignment capability is made possible by the design of the load-bearing plates that can be:

- Sharply crowned load-bearing plates
- Gradually crowned load-bearing plates
- Radiused load-bearing plates.

Sharply crowned designs use bearing plates that are thinner on the ends than in the middle, allowing the plate to rock around a pivot point at its center. This gives the bushing a misalignment tolerance of ±0.5° … and sharply crowned designs can carry higher loads — but also increase contact stress between the bearing plates and the bore. This can result in the bearing plate becoming embedded in the bore, which in turn increases the clearance between the shaft and the bushing.

Gradually crowned load plates operate on the same principle as sharply crowned designs but allow more contact area between the load plate and the bore, which reduces contact stress. This reduces the likelihood of the bearing plates becoming embedded in the bore, so the proper clearance is maintained between the shaft and the bushing. For this reason, gradually crowned versions are more common than sharply crowned designs.

The third bearing-plate design, sometimes called a radiused bearing-plate incorporates an outer ring along the center of the bushing housing. The ring provides a hardened surface for the bearing plates (which are flat rather than crowned) to contact. This design lets load plates self-align in all three directions of roll, pitch, and yaw. The downside of this design is that it requires more numerous and smaller balls to operate properly … which makes it more susceptible to damage or compromised operation due to dirt ingress or other contamination.



In this robotic gantry, twin linear bushings ensure precise linear motion.

Sealing is always a key consideration when specifying recirculating linear bearings, but it's even more critical with self-aligning linear bushings.

When a linear bushing tilts, a standard seal can lose contact with the shaft and become ineffective. To prevent this, self-aligning bushings are generally offered with floating seals, which maintain consistent contact with the shaft to ensure protection against contaminants. Floating seal designs also minimize seal friction.

Besides compensating for inaccuracies in mounting surfaces, alignment, or shaft deflection, self-aligning linear bushings also ensure even distribution of the load over the full length of the bushing. This prevents edge pressure between the end of the bushing and the shaft, for low friction and smooth running characteristics.

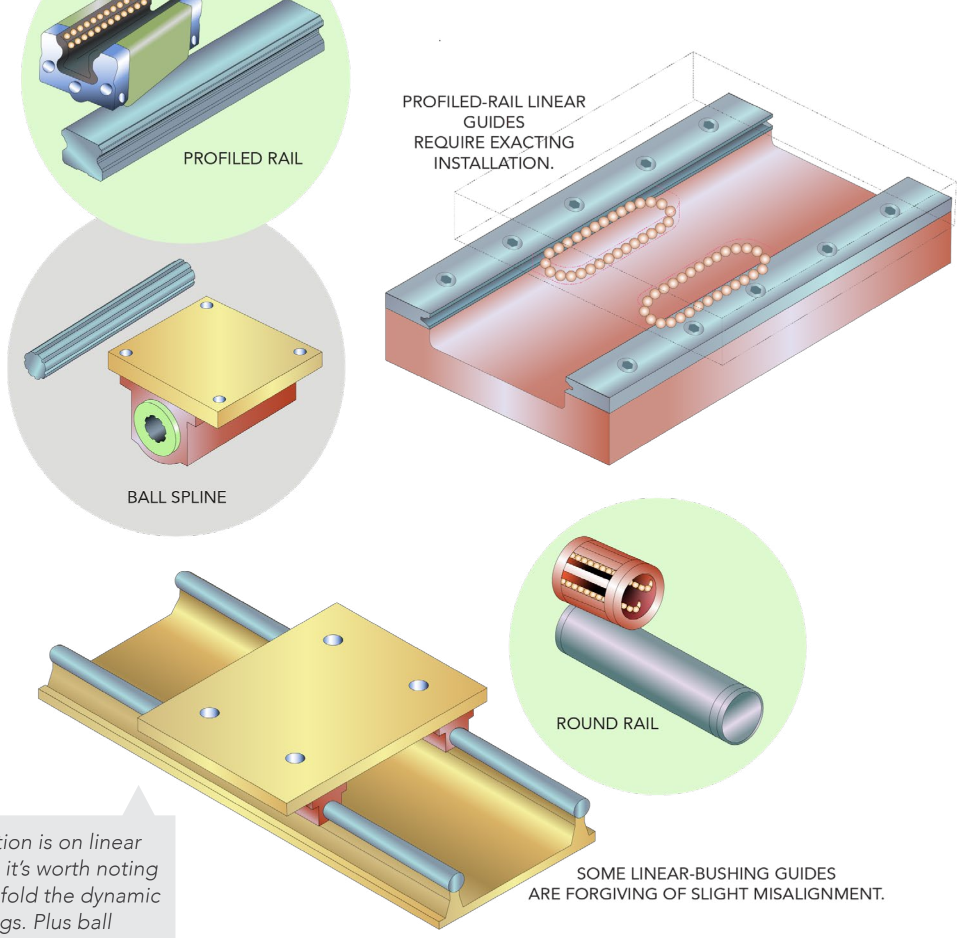
HOW TO CHOOSE BETWEEN **ROUND SHAFT OR PROFILED RAIL**

When designing a linear motion system, engineers have two primary choices in recirculating linear guides — round shaft or profiled rail. Choosing the wrong linear motion system can be a costly mistake … resulting in poor machine performance, the need to make design or structural changes, or oversized and overly costly components. Although both round shafts and profiled rails may appear to be suitable options for most applications, there are typically a few criteria that dictate [which technology is more appropriate](#).

Round shaft guides were invented in the 1940s and have been applied successfully in virtually every industry since their inception. But their limitations in rigidity forced manufacturers of precision equipment, such as machine tools, to use machined ways or cross rollers in order to achieve the required load capacities and accuracies. The introduction of profiled rail guides in the 1970s offered a less costly and less time-consuming alternative, providing high load capacity and high rigidity in a fairly compact envelope.

But for designers, the decision regarding when to use round shafts became less clear, because profiled rail guides were suitable for many of the applications that had been the province of round shafts. So design decisions were and sometimes still are based on past successes (or failures) with a given technology.

DIFFERENCE BETWEEN LINEAR BUSHINGS (ROUND RAIL LINEAR BEARINGS) AND PROFILED-RAIL LINEAR GUIDES



Note that the focus of this Design Guide section is on linear bushings compared to profiled rail. However, it's worth noting that typical ball splines can handle five to tenfold the dynamic load of comparable profiled-rail linear bearings. Plus ball splines can transmit torque and concurrently deliver low-friction load bearing during linear strokes.

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HOW TO CHOOSE BETWEEN ROUND SHAFT OR PROFILED RAIL

Fortunately, there are some key performance criteria that can guide the choice between round shafts and profiled rails — and take the guesswork out of the initial selection.

Load capacity — advantages of profiled rail: With conformity between the balls and raceways, profiled rail systems have a larger contact area, and thus a higher load carrying capacity for a given size, than round shaft systems. Profiled rails are also better suited for moment loads than round shafts are, and typically have equal load capacities in all four directions. Conversely, the load capacity for round shafts depends on the direction of loading, which is the orientation of the load to the ball bushing.

Rigidity — advantages of profiled rail: The larger contact area between the balls and raceways yields less deflection for a profiled rail system than for a round shaft. And while round shaft guides can be lightly preloaded, profiled rail systems are often supplied with preload ranging from 2 to 8% which provides further rigidity to the guide system.

Accuracy — advantages of profiled rail: With ground raceways and reference edges, profiled rails commonly achieve travel accuracies that are an order of magnitude better than round shaft guides. In these criteria, round shafts are more commonly valued for their ability to handle inaccuracies (self-aligning) than for their travel accuracy.

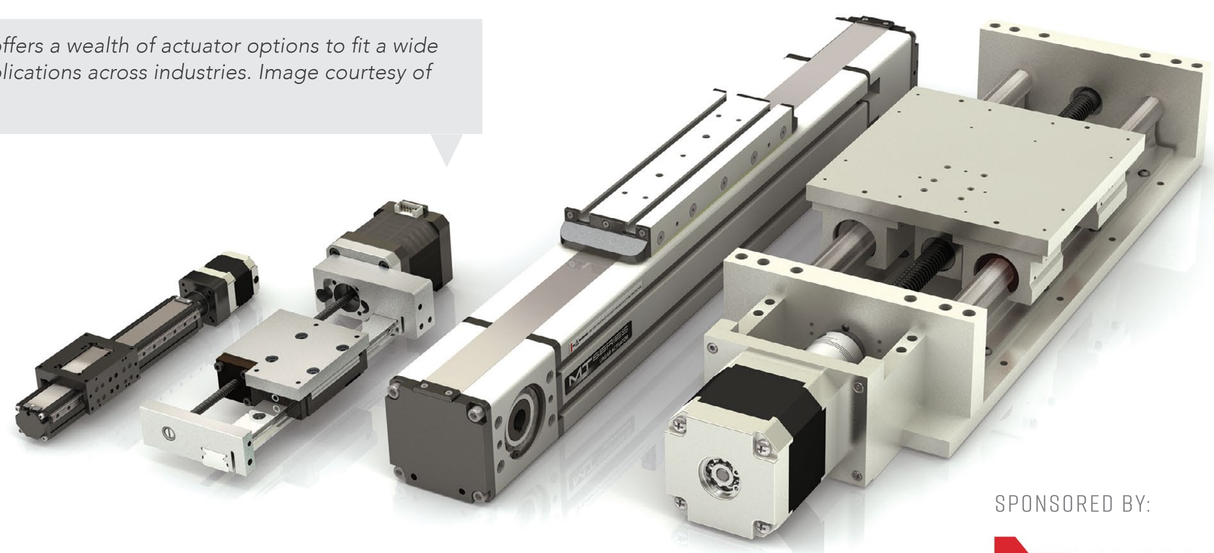
Speed — advantages of profiled rail: Round shaft guides can generally achieve a maximum speed of 2 m/sec being limited by the ability to control the balls as they move in and out of the load zone. Profiled rail bearings, with a more sophisticated recirculation method, can reach speeds of 5 m/sec.

Mounting — advantages of round shaft: Where profiled rail guides must be fully supported and mounted along their length, round shaft guides can be supported only on their ends, for lengths up to 20 times the shaft diameter. Round shafts also don't require machined surfaces for mounting, since ball bushings inherently compensate for some misalignment, reducing cost and time for designing and preparing mounting surfaces.

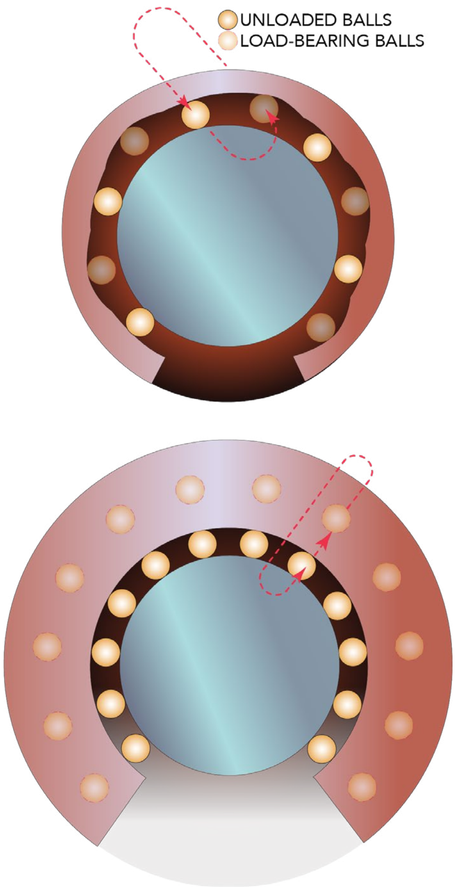
Harsh environments — advantages of round shaft: Round shafts are generally less sensitive to debris than profiled rails and are available in a variety of materials, coatings, and sealing options to withstand caustic or abrasive contamination. These range from all steel ball bushings to assemblies composed of stainless steel shafts with plastic bushings.

Maintenance — advantages of round shaft: Due to the smaller contact area between the load carrying balls and the running tracks, round shafts have less demanding lubrication requirements than profiled rails. Round shafts and ball bushings are also one of the few linear motion components that are, for the most part, interchangeable between manufacturers, which means that replacements are more readily available.

PBC Linear offers a wealth of actuator options to fit a wide range of applications across industries. Image courtesy of PBC Linear.



HOW TO MAKE SURE YOU GET THE RIGHT
LINEAR BUSHING INTERCHANGE



The type of ball recirculation – tangential (top) or radial (bottom) – affects the outer diameter and load capacity of a linear bushing.

Linear ball bushings are one of the few interchangeable product types in linear motion, with industry-standard sizes and styles, so that a product from one manufacturer can often be substituted with a product from another manufacturer that has very similar dimensions and technical specifications. And most linear bushing manufacturers offer several product lines that are dimensionally the same but have functional or performance differences. This means that if an application's requirements change or a product becomes unavailable, a nearly identical replacement bushing is typically easy to find.

LINEAR-BUSHING TYPE AND DIMENSIONS

The first step in the interchange process for linear bushings is to identify the type of bearing and its basic size. "Type" generally refers to whether the bearing is closed, for use on an unsupported shaft, or open, for use on a supported shaft. If the bearing is adjustable — meaning its diameter can be adjusted to reduce play or create preload — that should also be considered when determining the bearing type. The bearing size refers to the diameter of the shaft on which the bearing rides — 0.5 in. or 12 mm for example.

Although most linear bushing interchange tools base their selections only on bearing type and shaft diameter, the overall length and outer diameter of the bushing are important as well, especially in the case of an interchange, where the bushing is typically being mounted in an existing housing or framework. Depending on the number of ball circuits and the type of ball recirculation (tangential or radial), the outer diameter and overall length of the bushing can vary significantly, even for the same basic size (shaft diameter).

LINEAR-BUSHING SEALS AND WIPERS

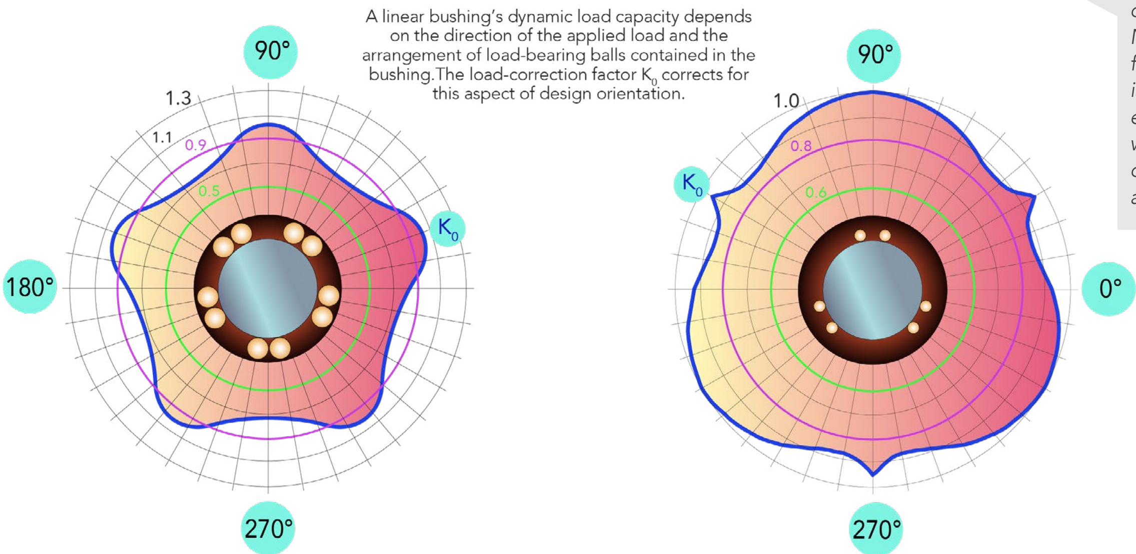
The next thing to consider is sealing. Does the bearing have seals on both sides, on one side only, or is it unsealed? Specifying the type of sealing is not only important for contamination protection, but also because seals add friction, which requires more force to move the bearing. External seals or wipers (which are often sold as separate parts but can sometimes be specified in the bushing part number) can also add length to the bearing, which is especially important to consider if the bearing is mounted in an existing housing or fixture.

LINEAR-BUSHING LOAD CAPACITY

To ensure that an interchange for an existing linear bushing is functionally the same, it's important to compare the load capacities of the old and new selections. Like overall dimensions, a bushing's load capacity is determined, in part, by the number of ball circuits and the type of ball recirculation. Even if all dimensions are the same or very similar, linear bushings of the same size can have significantly different load capacities. It's also important to remember that some ball bushings are rated for 50,000 m life, while others are rated for 100,000 m, so it may be necessary to apply a correction factor to the dynamic load capacity of one bushing in order to make a true comparison with another product.

THE MANY FACETS OF LINEAR BUSHING LIFE

POLAR GRAPHS TO PLOT
LINEAR BUSHING DYNAMIC LOAD CAPACITY



These are polar graphs showing orientation correction factors. Notice that the correction factor is highest when the load is between two ball tracks (for example at 90°) and lowest when the load is directly over one ball track — for example at about 50° or so.

Because linear bushings are the original recirculating linear ball bearings (with ensuring suitability for myriad industrial and consumer motion designs) manufacturers have extensive knowledge of how they behave in unconventional or challenging situations. No wonder there are extensive references to quantitatively predict linear-bushing performance in almost all design types.

Below are some of the most common factors that influence bushing life (including stroke length and shaft hardness) and an explanation of how to account for these factors during selection and sizing.

LINEAR-BUSHING LOAD ORIENTATION

Linear bushings are unique in that they can rotate around their shaft, which makes for some variability in the position of the ball tracks — and their load-carrying capability with it. Top load capacity is when the load is carried by the highest number of tracks possible. This means that the optimum bearing and load orientation depends on the number of tracks and whether the bearing is an open or a closed type.

To account for the various bearing and load orientation scenarios, most manufacturers provide polar graphs that give an orientation correction factor for each angle of deviation from a reference case. Other manufacturers provide a table showing correction factors for the two most common orientation cases — load applied directly above one row of balls, and load applied directly between two rows of balls.

The correction factors are specific not only to each manufacturer, but also to individual designs of linear bushings, so it's important to be sure that you have the right graph or table for the specific bushing in question. It's also important to note that the correction factor can be greater than one — meaning that in certain load orientations, the bearing's load capacity will be greater than the standard published load capacity … or less than one — reducing the published load capacity.

LINEAR BUSHING TRAVEL-LIFE EXPECTANCY

Like other recirculating bearings, the dynamic load capacity of a linear bushing is based on a predetermined travel distance — typically two million inches or 100,000 meters. One caveat here is that some manufacturers base dynamic load capacity on 50,000 meters.

Because linear bushings are often expected to achieve a travel life far exceeding the rated values, manufacturers provide a travel-life correction factor for the dynamic load capacity. For example, if the dynamic load capacity is based on 100,000 meters but the required life is actually 1,000,000 meters, a load-correction factor in the range of 0.4 to 0.5 may be necessary.

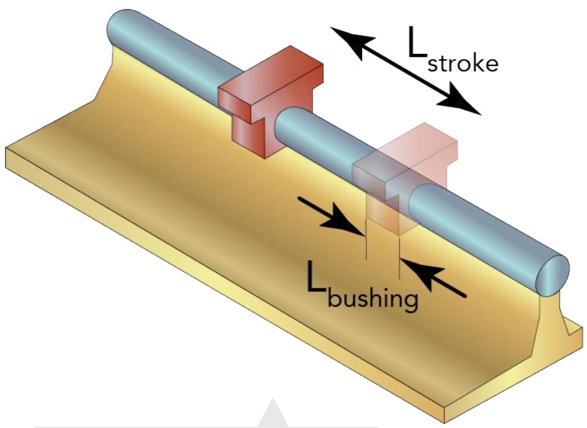
(continued)

THE MANY FACETS OF LINEAR BUSHING LIFE

LINEAR BUSHINGS WORKING OVER SHORT STROKES

If a linear bushing travels only a short distance, the repeated wear, concentrated on a small area of the shaft, will reduce the life of the shaft in comparison to the life of the bushing.

This situation is known as a short stroke application and is typically defined as a stroke that is less than two (or for some manufacturers three) times the length of the bushing. In these applications, a short stroke correction factor must be applied to the dynamic load capacity of the bushing.



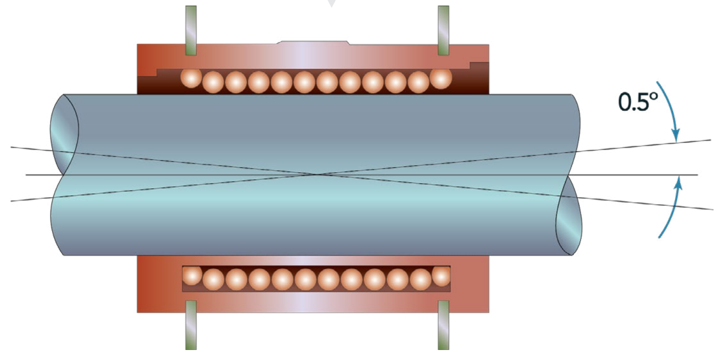
A short stroke is defined as one that is less than two (or for some manufacturers three) times the length of the linear bushing.

SHAFT HARDNESS IN LINEAR BUSHINGS

Unlike their profiled-rail linear-bearing counterparts, linear bushings and shafts aren't matched sets. That means the bushing and shaft can each be supplied by different sources. Linear bushing manufacturers commonly provide steel shafting with a hardness of HRC58 or HRC60. But when shafting is obtained from an alternative source (or if a different composition is used) the hardness can vary.

Case in point: 420 stainless steel can have a hardness as low as HRC51, while 440C stainless can have a hardness of HRC61. Here, a shaft-hardness correction factor must be applied, to account for accelerated wear due to the softer material. Note that shaft harness correction factors are typically given for both dynamic and static load capacities.

When any shaft deflects, misalignment occurs between the axis of the shaft and the axis of the bushing.



MISALIGNMENT IN LINEAR-BUSHING INSTALLATIONS

Another example is a misalignment factor. When shafts aren't supported along their entire length, they can experience deflection … and that in turn which causes misalignment of the bushing relative to the shaft. This is especially problematic if the bushing is not a self-aligning type, as it results in uneven loading on the load-carrying balls.

If misalignment exceeds a given value (but remains below the maximum allowable misalignment) then a misalignment factor must be applied to the dynamic load capacity.

Self-aligning pillow blocks from PBC Linear combine straight OD bearings with standard pillow block housings that supply ½° of self-alignment in all directions. Image courtesy of PBC Linear.

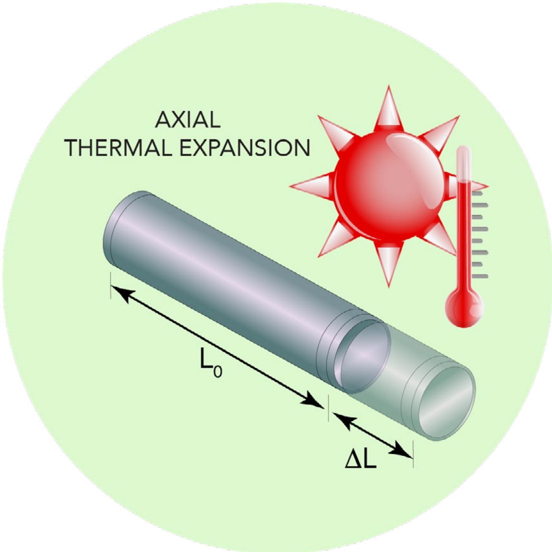
(continued)

THE MANY FACETS OF LINEAR BUSHING LIFE

THERMAL CONSIDERATIONS FOR AXES USING LINEAR BUSHINGS

One more consideration for linear bushings is temperature. Seals and other plastic components in linear bushings often limit their use to temperatures up 85° C — or (for specialty components specifically designed for hotter environs) 100° C. Some linear bushings with higher-temperature capabilities include all metal components.

But wherever an all-metal design is impractical, a temperature correction factor can be applied to account for accelerated wear and reduced life. Similarly, correction factors are sometimes given for applications with high shock loads or vibration.



The coefficient of linear thermal expansion expresses the material's rate of expansion ΔL per unit length L_0 — and per degree temperature change ΔT.

After all, it's nearly impossible to construct a linear system from just one type of material … so it's key to understand how various thermal-expansion rates for various components can lead to inaccuracies, poor performance, and even failure of the system.

In fact, thermal expansion affects all linear guide systems, and most materials used in linear systems have a positive linear thermal-expansion coefficient. In other words, upon temperature increase there is an expansion in length … and temperature decreases cause axial contraction.

More specifically, a material's tendency to expand or contract with temperature change is given by its coefficient of linear thermal expansion α — which expresses the material's rate of expansion ΔL per unit length L0 or per degree temperature change ΔT.

$$\Delta L = \alpha L_0 \Delta T$$

Where ΔL = change in length

α = Coefficient of linear thermal expansion

L_0 = Original length

ΔT = Change in temperature

Because the rate of expansion is very low, α is often expressed as parts per million per degree Celsius (ppm/°C) or parts per million per degree Fahrenheit — ppm/°F. However, the SI unit for α uses the kelvin temperature scale and is simply expressed as K-1 or 1/K.

Sources of heat that influence linear bearing temperature can be both external and internal. The most obvious source of heating (or cooling) is the ambient environment. But any moving parts that experience friction (including ball or leadscrews, rack and pinion sets, gearboxes, and even motors) generate heat …

… and much of this heat is directly transferred to the machine or to the surface on which the guide rails are mounted. The guides themselves also generate heat internally, due to preload and friction between the bearing and the guide rail or shaft.

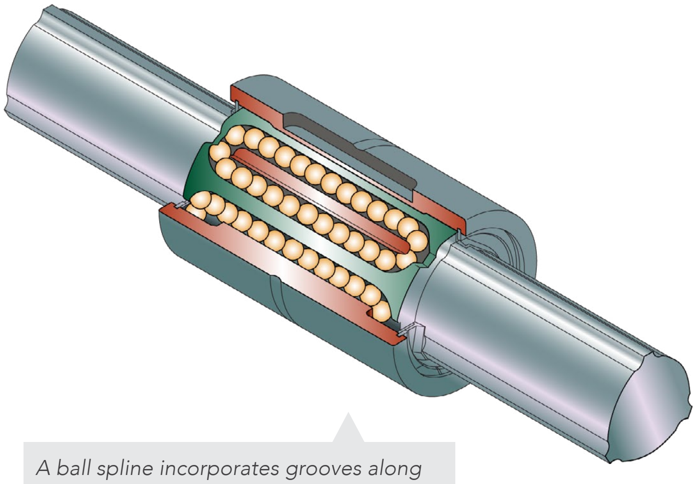
BASICS OF BALL-SPLINE AND ROTARY BALL-SPLINE APPLICATIONS

As covered earlier in this Design Guide, ball splines are a type of rolling-bearing linear guide. They're much like linear bushing (round shaft and bushing) assemblies but with a critical distinction in their operation.

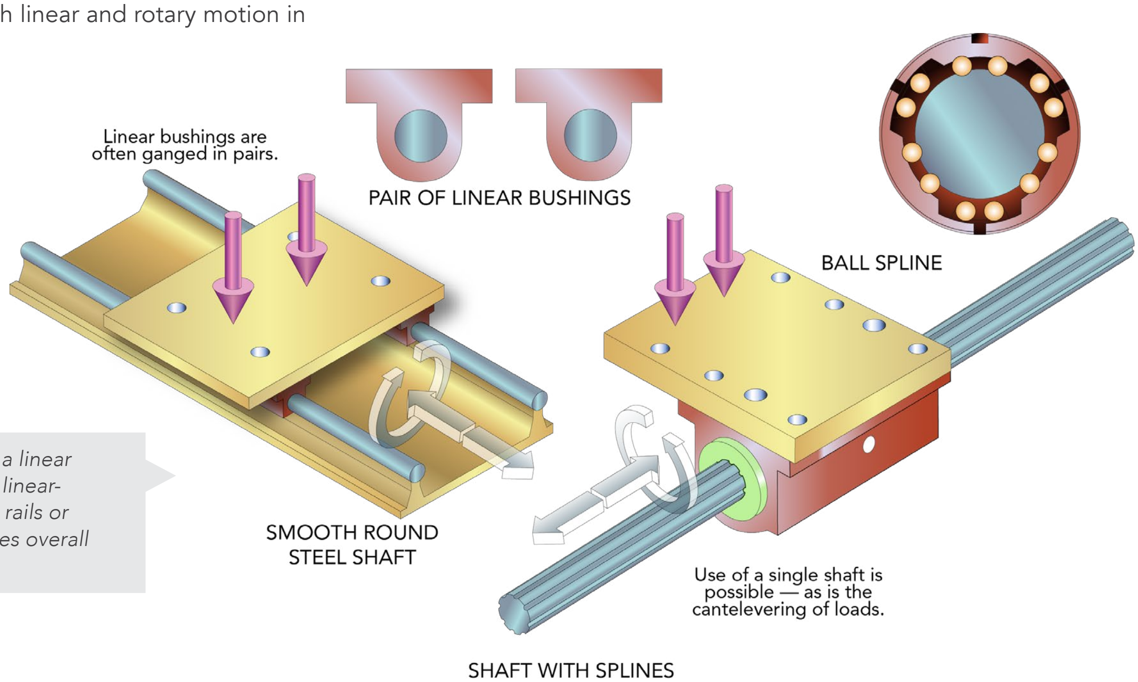
The ball-spline shaft is much like a linear-guide shaft except that the spline shaft has grooves along its length. The spline nut (analogous to the bearing, or bushing, of a traditional rolling bearing guide) contains circuits of recirculating balls. But instead of the spline nut riding freely on the shaft with the ability to rotate during linear travel, the load-carrying balls ride in the shaft grooves that constrain the spline nut and totally prevent rotation.

Another version of the ball spline is the rotary ball spline, which incorporates a rotating element — such as an angular contact ball bearing, crossed rollers, or gear teeth — on the outer diameter of the nut. This adds the capability of rotary motion to the linear motion provided by the ball spline — somewhat like a cross between a recirculating linear guide and a ballscrew.

Because the recirculating balls of the spline nut ride in grooves, the contact area is greater than for ball bushings, giving ball splines much higher load capacities than ball bushing assemblies of the same size. But even though higher load capacity is a benefit, the primary reason many designers and engineers use ball splines is their ability to prevent rotation or (in the case of rotary ball splines) to provide both linear and rotary motion in one device.



A ball spline incorporates grooves along the length of the shaft and on the inner surface of the spline nut to prevent rotation and transmit torque.



Unlike the straightforward design of a linear system based on a ball spline, other linear-bearing types often necessitate twin rails or mechanisms … which in turn increases overall design complexity and size.

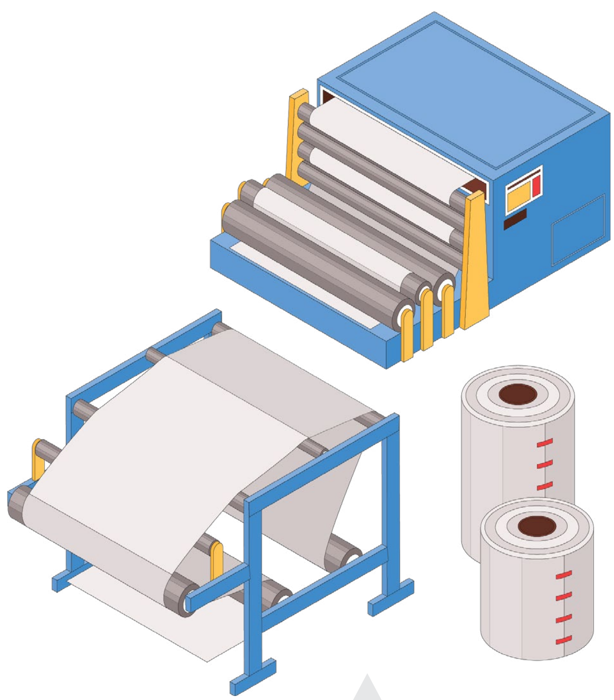
(continued)

BASICS OF BALL-SPLINE AND ROTARY BALL-SPLINE APPLICATIONS

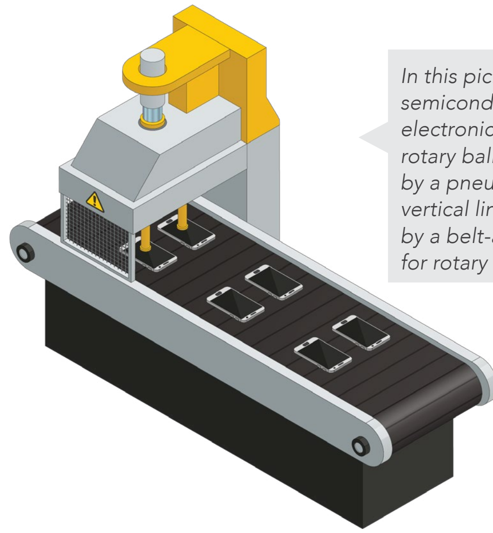
Traditional linear bushings are almost exclusively used in dual-shaft configurations to prevent the bearings from rotating as they ride on the shafts. But since ball splines are inherently anti-rotation, they can be used in single-shaft configurations. And replacing two shafts with one also means a smaller footprint, less weight, and easier alignment and assembly.

> The ball-spline shaft is much like a linear shaft-and-bushing assembly except that the spline shaft has grooves along its length.

Linear and rotary motion in one: Rotary ball splines also provide excellent solutions for Z-theta axes on SCARA robots. The spline shaft provides the Z (vertical) movement. The rotary bearing on the spline nut then provides the θ rotational movement.



In this paper-manufacturing application example, ball splines excel. The spools of paper need the freedom to move horizontally left to right but shouldn't spin freely. Preventing rotation with traditional linear shafts would necessitate a higher component count … in contrast with a single ball-spline shaft that supports the load to allow horizontal movement while preventing rotation.



In this pick-and-place semiconductor (consumer electronics) application, a rotary ball spline is driven by a pneumatic cylinder for vertical linear motion — and by a belt-and-pulley system for rotary motion.

These properties also make rotary ball splines suitable for automatic tool changers in CNC machine tools.

Pick-and-place or assembly applications also make copious use of rotary ball splines. Consider how transferring a workpiece from one station or conveyor to another might involve:

- Picking the part from the first station — with vertical motion
- Rotating to the position of the second conveyor — with rotary motion
- Placing the part on the second conveyor — with vertical motion

In this case, a rotary ball spline can be driven by a pneumatic cylinder (for the linear motion) in conjunction with a belt-and-pulley system for the rotary motion.

Ball-spline designs fall into two categories — those for torque transfer and those for combined linear and rotary motion. Ball splines for torque transfer abound in machinery for product assembly, welding and plating, wire winding, paper processing, and material handling. In contrast, ball splines for combined linear and rotary motion abound in pick-and-place robotics, water jets, automatic tool changers, laboratory equipment needing quick transfers of pipettes and other test samples, and packaging equipment.

Ball splines for torque transfer: A ball spline is essentially a linear bushing and shaft pairing … except with both the axial shaft and the nut ID sporting axial grooves … hence the term *spline*. Load-carrying balls recirculate within the nut just as they do in a linear bushing. However, the grooves in the shaft prevent rotation and facilitate the transmission of torque. This allows ball splines to withstand overhung loads and moment loads, unlike linear bushings, which can only support radial loads.

(continued)

BASICS OF BALL-SPLINE AND ROTARY BALL-SPLINE APPLICATIONS

As mentioned earlier in this Design Guide, the ball-spline assembly's part housing the recirculating balls is called a nut — and not usually called a bushing. Even this terminology is somewhat imperfect though … as a ball-spline nut's functionality is indeed different from that of a ballscrew's recirculating-ball nut.

Because the design of a ball spline affords much greater contact area between the balls and the grooves than that of standard bushings, ball splines have significantly higher load capacities. Ball splines typically have two, three, or four grooves … although some designs have up to six grooves. Like the raceways of profiled rail bearings, the grooves in a ball spline can be designed with either:

- Circular arch geometry for two-point contact on each ball

or

- Gothic-arch geometry for four-point contact on each ball.

Refer to the final section of this Design Guide for more on this topic. Essentially, Gothic arch geometry provides higher rigidity but also contributes to higher friction. In contrast, circular arch geometry has lower friction and smoother running characteristics. Torque capacity is determined by the number of contact points, so a ball spline with four Gothic arch grooves will have 16 contact points and transmit more torque than an otherwise identical component with two Gothic arch grooves and just eight contact points.

Sizing and selection of ball splines combines technical considerations from both linear recirculating bearings and ballscrews. Life is calculated via the standard bearing life equation, using both radial loads and torque loads. Like profiled rail guides, ball splines can be preloaded to increase rigidity and provide better support for moment loads.

Ball splines are fixed with rotary bearings much like ballscrews, and the end fixity (such as fixed-fixed or fixed-floating and so on) influences critical speed — as do the shaft root diameter and unsupported length. Accuracy grades are also assigned to ball splines in a way that's similar to those assigned to ballscrews — based on:

- Radial runout and perpendicularity of the shaft ends
- Radial runout of the nut body
- Perpendicularity of the nut flange (where applicable).

However, ball-spline accuracy classes aren't based on industry standards such as DIN or JIS. That means one manufacturer's "top-precision" accuracy class may be similar to another manufacturer's middle-of-the-road accuracy class.

Rotary ball splines for combined linear and rotary motion: While recirculating linear bearings provide linear motion and ballscrews provide rotary motion, rotary ball splines fill the gap between the two — generating both linear and rotary motion.

Rotary ball splines incorporate a rotating element — angular contact ball bearings, crossed rollers, or gears — on the outer diameter of the nut. This provides rotary motion in addition to the linear motion of the ball spline itself.

Both standard and rotary ball splines are offered with a hollow spline shaft, which helps with integration into systems such as SCARA robots … allowing electrical or pneumatic lines to route through the spline shaft. In fact, one of the most common applications for rotary ball splines is the Z-theta axis of SCARA robots.

HOW TO CALCULATE LINEAR BALL BUSHING LIFE

(AND HOW IT DIFFERS FROM OTHER LIFE CALCULATIONS)

The standard life calculation for linear ball bearings is widely known as:

$$L = \left(\frac{C}{F}\right)^3 \times 10^5$$

L = bearing life (m)
C = rated dynamic load (N)
F = applied dynamic load (N)

But linear ball bushings often experience operating conditions that aren't accounted for in the general bearing life equation. To account for these adverse conditions, the life calculation for linear ball bushings includes a number of correction factors that adjust the bearing life accordingly.

$$L = \left(\frac{C}{F} \cdot K_\Theta \cdot K_S \cdot K_T \cdot K_C\right)^3 \times 10^5$$

Here, we'll look at each of these correction factors and explain how and when to use them.

The first correction factor (**K_Θ**) accounts for the orientation of the load relative to the ball tracks, or circuits, in the linear bushing. When a load is applied to a linear bushing assembly, the orientation of the bushing on the shaft and the direction of loading determine whether the load is carried by just one ball track or shared between two or more tracks.

To account for this variability, manufacturers offer charts or polar graphs that provide load correction factors depending on the orientation of the load relative to the orientation of the ball tracks.

Unlike other correction factors, the load correction factor can be greater than 1.0 in some cases, meaning that a specific load-bushing orientation provides a dynamic load capacity that is higher than the published value.

SHAFT HARDNESS

In a recent article, we looked at how the hardness of the shaft can affect the life of a linear bushing assembly. Manufacturers typically recommend that shafts used with linear ball bushings have a hardness of 58 to 60 HRC. If the shaft hardness is lower than recommended, a shaft hardness factor (**K_S**) must be applied to de-rate the bearing's dynamic load capacity, and in turn, the bearing's expected life.

TEMPERATURE

Very high operating temperatures can affect the integrity of the components that make up the bushing — such as seals and load plates — and can also reduce the shaft hardness. A temperature correction factor (**K_T**) takes into account this degradation in material and typically comes into play for operating temperatures above 100° C.

SHORT STROKE

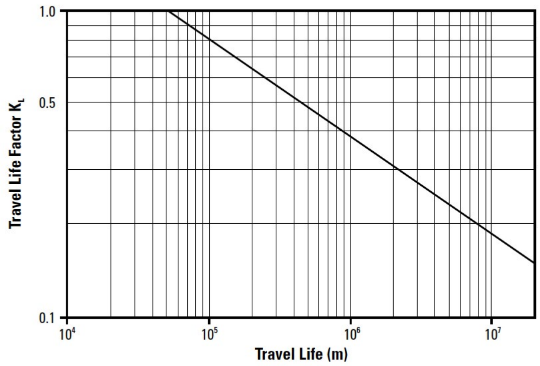
When the stroke of a linear ball bushing is very short — between 1.5 and 3 times the length of the bushing, depending on the manufacturer and bearing type — the application is often considered a "short stroke" application. In these conditions, the shaft may experience accelerated wear and premature failure, since a small area of the shaft must continually withstand the forces and pressure created by the load-carrying balls. The short-stroke factor (**K_C**) takes this into account and reduces the bearing life accordingly.

LIFE FACTOR

The bearing life equation determines the expected life of linear ball bushing for a given dynamic load capacity and applied dynamic load. But in some cases, the desired bearing life and the applied load are known, and the parameter to be calculated is the required dynamic load capacity of the bushing that will provide the specified bearing life under the given load. In this case, the required dynamic load capacity (CR) is calculated as follows:

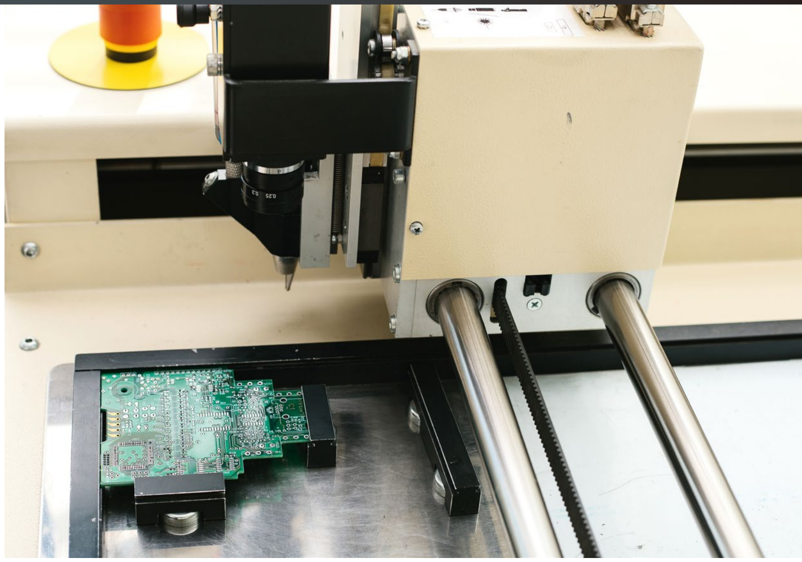
$$C_R = \frac{F}{K_S \cdot K_T \cdot K_L}$$

But recall that the bearing life for a linear ball bushing is based on 100,000 m (or 2 million inches for inch products). If the desired bearing life is greater than 100,000 m (or 2 million inches), the applied load must be divided by a life factor (**K_L**) in order to account for the longer bearing life.



WHAT MAKES A LINEAR GUIDE

SUITABLE FOR HIGH TEMPERATURE USE?



For most recirculating ball and roller linear guides, the allowable operating temperature range is -10° to 80° C, with some configurations rated up to 100° C for brief periods. But not all applications fall within this temperature range, and each component in the linear bearing assembly (housing, rail, balls, seals, etc.) has a different maximum and minimum operating temperature. But if you choose the right metal components, plastic components, lubrication, and optional accessories, you can configure a recirculating linear guide that can withstand high (or low) temperature applications that fall outside the standard -10° to 80° C range.

METAL COMPONENTS

The metal parts of a recirculating linear guide include the bearing housing, recirculating balls or rollers, guide rail, scraper plates, and various fastening and mounting screws. The makeup of these parts can encompass three or more different types of steel, stainless steel, and — in some cases — aluminum. So it's important to understand which type of metal each component is made of and what temperature range it can withstand.

In many cases, manufacturers recommend using stainless steels wherever possible when the application falls outside the normal operating temperature range, especially if the temperature is very high (above 150° C) or very low (below 0° C). One of the reasons for this recommendation is the possibility of temperature fluctuations, which can cause condensation and lead to corrosion.

PLASTIC COMPONENTS

Plastics parts, such as seals and recirculation components, are often a limiting factor in terms of the temperature suitability of a recirculating linear bearing. However, linear guide manufacturers offer seals made of special materials, such as FPM or FKM (fluorinated rubber, commonly known as Viton, from DuPont), with extended operating temperature ranges.

If the environment doesn't present liquid or solid contamination, another option is to use a linear guide with only metal seals. And although forgoing seals altogether isn't recommended for profiled linear guides (because they help to keep lubrication inside the bearing), round shaft linear guides and cam roller slides can be operated without seals, making them another option for applications that don't call for the load capacity or rigidity of a profiled linear guide. And since these designs don't require plastic recirculation components, they're available in all-metal versions that can withstand temperatures outside the range of most plastics.

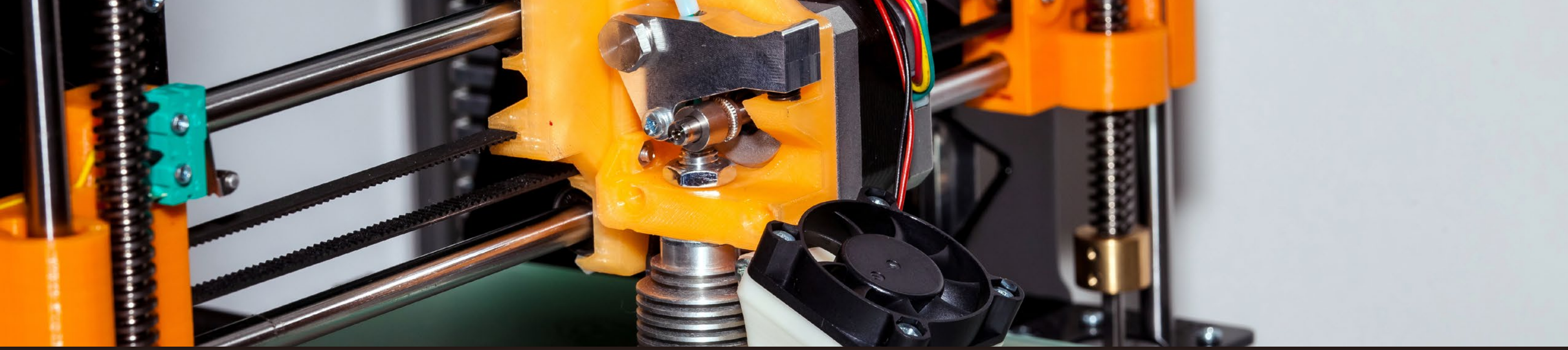
LUBRICATION

Temperature also affects the performance of lubrication in a recirculating linear guide. Specifically, the temperature of a lubricant affects its viscosity (resistance to flow), and grease lubrication that exceeds its rated temperature can separate into its components (base oil, thickener, and additives), reducing its effectiveness.

In general, lubricants with a lower viscosity are recommended for low-temperature applications, while higher viscosity lubricants are best for high-temperature applications. And keep in mind that in addition to the type of lubrication to use, the recommended lubrication interval is also affected by the operating temperature of the bearing.

OPTIONAL COMPONENTS AND ACCESSORIES

Temperature limitations also apply to optional components, such as additional seals, external lubrication units, and cover strips or bellows. For example, recirculating linear guides are typically rated for use at temperatures up to 80° C, but external lubrication units often have a maximum temperature rating of 50° to 60° C. Sensitive components such as measuring systems (integrated linear encoders) and parts that are integral to the recirculation system, such as ball chains or ball separators, should also be checked to ensure they can withstand excessively high or low operating temperatures.



WHICH LINEAR GUIDES ARE INTERCHANGEABLE?

The need to replace a linear guide in an existing machine or assembly can arise for any number of reasons: to improve the stiffness of the assembly by changing to a bearing with higher preload, or to accommodate unforeseen space constraints by using a different bearing type or style. And sometimes, a linear guide needs to be replaced simply for maintenance and repair.

> In this context, "style" refers to the general shape of the bearing block—its length (standard, short, or long), width (standard or wide), and whether it has flanges or not. "Style" can also refer to how many rows of balls the bearing has—two, four, or six.

Regardless of the reason for an interchange, the process of changing a linear bearing isn't always as simple as ordering a new component and installing it on the machine. For some products, components from different manufacturers cannot be interchanged, regardless of their style or size. And even within a given manufacturer's product line, not all components are interchangeable. Before you make an attempt to replace a linear bearing, shaft, or rail, here's a guide to what types are (and are not) interchangeable and what dictates their interchangeability.

ROUND SHAFT GUIDES

Interchanging round shaft guides is a straightforward process, due to their simple geometry and small range of materials and hardness ratings. Their primary specifications are diameter, diameter tolerance, and shaft hardness. As long as those three parameters match, or are suitable for the application, any shaft from any manufacturer can be used with any plain or recirculating bearing of the same size.

PROFILED RAIL BEARING BLOCKS

Due to geometric and dimensional differences in the raceways of the bearing and guide rail, it's impossible to use a profiled rail bearing from one manufacturer with a guide rail from another manufacturer. So if only one component (either bearing or rail) needs to be replaced, it must come from the same manufacturer as the original.

On the other hand, if both components need to be replaced, it is possible, in some cases, to interchange an entire assembly from one manufacturer to another. This is because some of the most frequently-used sizes and styles of profiled rail assemblies have the same outer dimensions (height, width, mounting bolt pattern) between manufacturers.

> Manufacturers sometimes use the term "random matching" to indicate that products within their profiled rail linear guide offering are interchangeable.

When changing from one profiled rail bearing to a different style or preload within a manufacturer's product line, keep in mind that interchangeability is not always provided for in the design. This is because in order to "mix and match" different bearing blocks and rails of a given size, the positions of the raceways on both the rail and the bearing block must be very precisely controlled. Very often, preloaded bearing blocks are not interchangeable, because tolerances between the guide rail and the bearing affect the preload amount.

PROFILED RAIL GUIDES

In the same manner as profiled rail bearing blocks, profiled rail guides are not interchangeable between manufacturers. However, within a manufacturer's product line, profiled rail guides can typically be interchanged, as long as they are of the same style—meaning the number and design of the raceways is the same.

TWO FACTORS TO CONSIDER WHEN SELECTING SHAFTS FOR LINEAR BEARINGS

In a round shaft linear bearing system, the shaft acts as the inner raceway of the bearing and plays a significant role in the wear and life of the system.

Both recirculating and plain linear bearings based on round shaft can use a wide variety of shaft materials, depending on the application or environmental requirements. Shafts for recirculating linear bearings are typically made of bearing-grade carbon steel or stainless steel. Likewise, plain linear bearing systems can use carbon steel, stainless steel, or aluminum shafts. And for very harsh environments or special conditions, shafts can be plated or coated to withstand caustic or abrasive contaminants.

When choosing which type of shaft to use in a linear bearing application, the two most important factors that contribute to bearing wear and life are the shaft's surface finish and hardness.

SURFACE FINISH IN ROUND-SHAFT LINEAR BEARINGS

Surface finish generally refers to the "roughness" of a surface, which is a measure of how much the surface topography varies from an ideal plane. Recirculating ball bearings operate best when paired with ground or polished shafts with a low roughness value. This is because a better surface finish actually increases the contact area between the shaft and the recirculating balls. A "rough" shaft surface, with a significant number of peaks and valleys, provides less contact area for the balls to ride on, whereas a smoother shaft surface provides more contact area for the load-carrying balls. Typical surface finish recommendations for shafts used with recirculating ball bearings are 6 to 10 microinch Ra.

For plain linear bearings, however, a smoother shaft surface can actually lead to decreased life, due to the self-lubricating nature of most plain bearings. Plain bearings rely on features of shaft roughness — specifically, the "peaks" on the surface of the shaft — to transfer small amounts of the bearing material to the shaft. These dislodged bits of material fill in the valleys on the shaft surface and provide lubrication as the bearing travels back and forth. Without this lubrication, friction between the shaft and bearing will be higher, and the bearing's PV rating will be reduced.

This is also true for plain bearings made of bronze, which must be lubricated externally. A slight roughness of the shaft surface helps the shaft retain lubricant and prevent metal-to-metal contact. But as with recirculating bearing shafts, a surface that is too rough can also cause extensive wear on the bearing and lead to premature failure. The suggested range of surface roughness values depends on the bearing material, but as an example, composite bearing manufacturers generally recommend a shaft surface roughness of 8 to 16 microinch Ra.

Surface roughness can be expressed in terms of Ra or RMS, both of which are defined in ASME B46.1. Ra or average roughness is the arithmetic mean of the absolute values of the profile deviations from the mean line of the roughness profile. RMS roughness is the root mean square average of the profile height deviations from the mean line. Both measurements can be expressed in metric (micron) or inch (microinch) units. The Ra measurement is more commonly used today, although some manufacturers still use RMS roughness measurements. Because they are calculated with different formulas, there is no direct conversion between Ra and RMS.

(continued)

TWO FACTORS TO CONSIDER WHEN SELECTING SHAFTS FOR LINEAR BEARINGS

SHAFT HARDNESS IN LINEAR BEARINGS

Equally important to shaft surface finish is the shaft hardness. Sufficient shaft hardness is critical for recirculating linear bearings because point loading created by the balls can cause permanent deformation of the shaft. Because heavier loads place more stress on the surface of the shaft, they require higher hardness values than lighter loads. In fact, a shaft hardness factor often denoted H or f_H is included in load and life calculations for recirculating ball bearings.

The typical hardness recommendation for round shafts used with recirculating ball bearings is HRC 60, which corresponds to a shaft hardness factor f_H of 1.0 — in other words, with no increase in required load capacity or reduction in life.

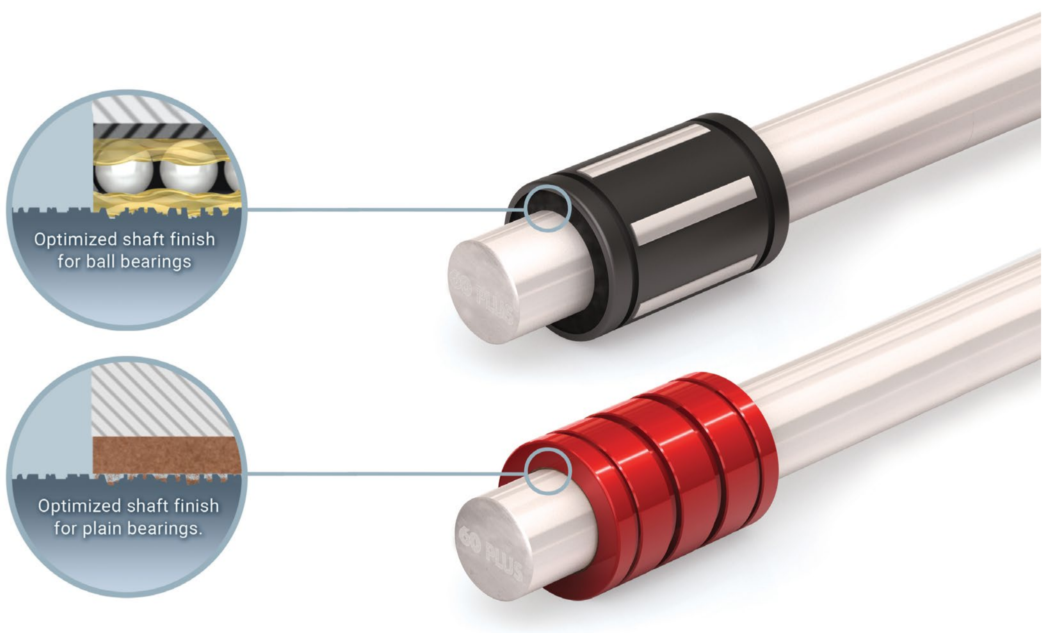
Hardness ratings below HRC 60 can significantly reduce the life of the bearing assembly. Note that stainless steel generally has a hardness value in the range of HRC 54, meaning assemblies that use stainless steel shafts will have a lower life expectancy, even if all other operating parameters are the same.

Although shaft hardness is not as critical for plain linear bearings as it is for recirculating types, it does play a role in plain bearing wear. Because plain bearings don't typically include seals or wipers, contaminants can become trapped between the bearing and shaft and, if the bearing material is soft, the contaminants can become embedded in the bearing.

Likewise, if the shaft hardness is not sufficient, contaminants can also become embedded in the shaft. For example, Dupont demonstrates that bearings made of its Delrin® acetal resin experience less wear and better life when used with harder shafts. And for plain bearings made of bronze, the shaft material must be harder than the bearing material.

The Rockwell C scale is typically used to quantify the hardness of linear bearings and shafts, although the Rockwell B scale is sometimes used for softer materials such as bronze and aluminum.

The right amount of microscopic surface texture on Simplicity 60 Plus Shafting holds lubrication for consistent ball rotation, and the Frelon® break-in and transfer process for Simplicity plain bearings. Image courtesy of PBC Linear.



WHAT ARE RECIRCULATING LINEAR BEARINGS?

Linear ball and roller bearings can be broadly divided into two categories—recirculating and non-recirculating—depending on whether or not the rolling elements actually flow (or circulate) through the bearing housing. In order to understand what a recirculating linear bearing is, let's first take a look at bearings that don't recirculate.

NON-RECIRCULATING LINEAR BEARINGS

Non-recirculating bearings have balls or rollers that are contained in a housing and directly support a load. As the bearing moves, the rolling elements rotate about their own axes, but they do not travel within the housing. Although their basic construction principle is the same, there are several types of non-recirculating bearings, based on the type and arrangement of their rolling elements, as shown below.

Regardless of their different rolling mechanisms and designs, all non-recirculating bearings have a few things in common. First, the length of the bearing and the number of rolling elements limits the stroke that can be achieved. Second, because their rolling elements only rotate (no recirculation), they provide extremely smooth motion. And with machined top and bottom surfaces, they can have extremely high travel accuracy. Non-recirculating bearings are often the guide system of choice for high-precision stages and are commonly used in machine tool, precision scanning, and measuring applications.

RECIRCULATING LINEAR BEARINGS

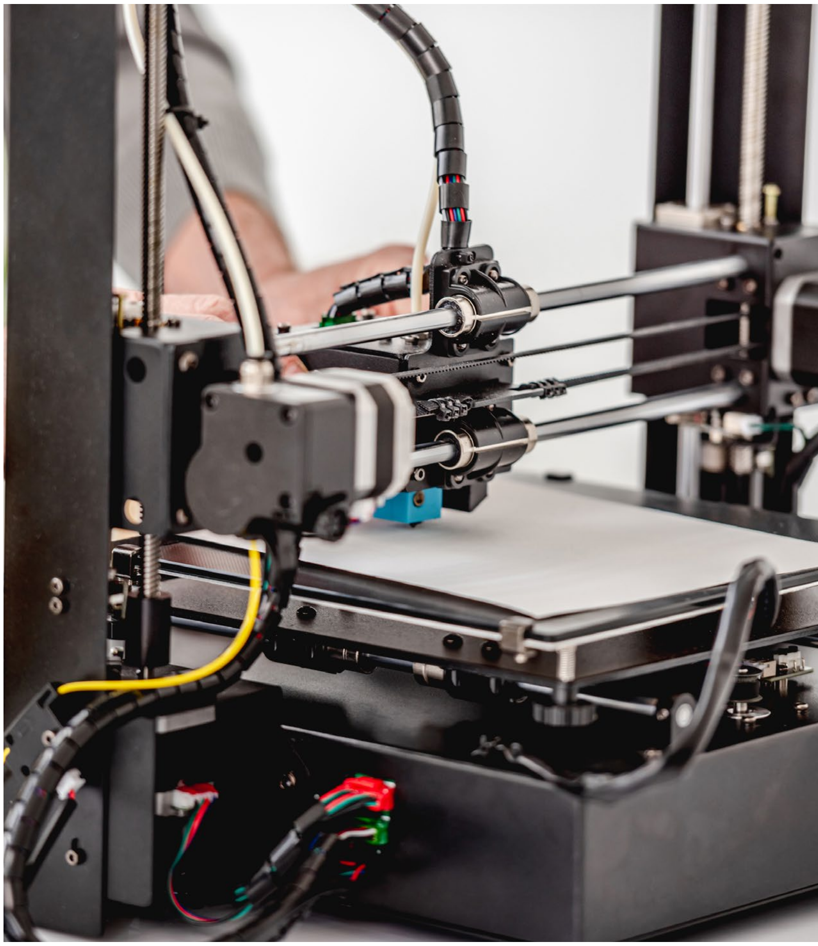
"Circulate" means "to move in a circle or circuit; to move or pass through a circuit back to the starting point." And the term "recirculate" means to do this over and over again. Hence, recirculating bearings have rolling elements that move continuously through a circuit, or path, within the bearing. This design allows the bearing to travel any distance, regardless of the bearing length. In other words, where non-recirculating bearings have limited travel, in theory, recirculating bearings have unlimited travel, constrained only by the length of the rail or shaft guideway.

Recirculation does present some challenges though. First, as the balls or rollers circulate through the bearing, they move from a non load-carrying zone (sometimes referred to as the return zone) to a load-carrying zone. This variation of the balls (or rollers) from a non-loaded to a loaded state causes pulsations, which affect the bearing's travel accuracy.

Improving the smoothness of the circulation process has been a priority for manufacturers in recent years, with new designs for the recirculation zone yielding improved travel accuracies.

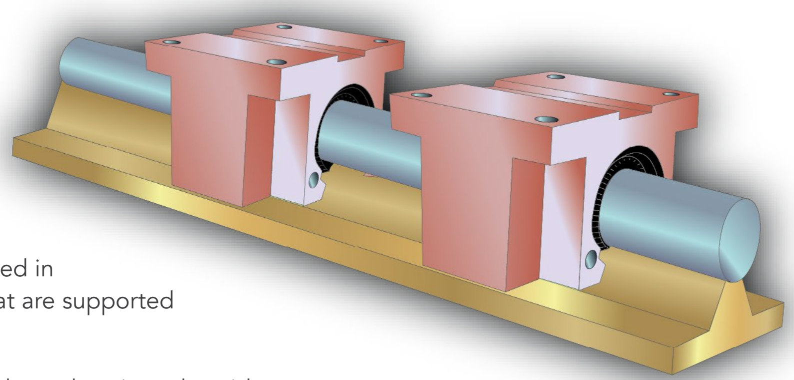
Recirculation also limits the maximum speed that the bearing can achieve, due to the forces created on the bearing end caps when the recirculating elements make the "turn" around the circuit. One way to reduce these forces is to reduce the mass of the balls. Some manufacturers have done just that by offering profiled rail bearings with ceramic balls. These versions can achieve speeds up to 10 m/s, but with a somewhat reduced load capacity.

Although recirculating bearings generally have lower travel accuracies than non-recirculating types, they come in a wide range of sizes, preloads, and accuracy classes, making it easy to find a recirculating linear bearing that fits just about any application requirement.



TIPS FOR MOUNTING LINEAR BALL BEARINGS: PILLOW-BLOCK HOUSINGS

Linear ball bearings and round shafts are often used in applications that call for ease of use and simple mounting requirements. For example, where profiled rail guides require full support along their length, linear ball bearings, or bushings, can be used in many applications with shafts that are supported only at their ends.



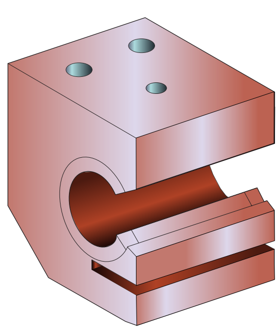
The inner diameter of the pillow block affects the clearance between the bearing and shaft. Too much interference can reduce bearing life, while too much clearance can reduce load capacity and rigidity.

However, unlike profiled rail guides or bearings that ride on spline shafts, linear ball bearings have no built-in mechanism that prevents them from rotating around the shaft, so they're typically mounted in a bearing housing. This housing, or pillow block, also facilitates mounting the external load to the bearing.

Like linear ball bearings, pillow blocks are available in both closed and open versions, with open versions being suitable for use on shafts with support rails. Various materials are also available — including aluminum, cast iron, and stainless steel, depending on the application's requirements for rigidity and use in harsh environments. Plus to facilitate easier mounting and alignment of multiple bearings, some aluminum pillow blocks come in twin or tandem versions, allowing two bearings to be mounted in one housing.

The amount of clearance between the bearing and shaft is an important factor in bearing performance and is determined by a combination of factors — the radial clearance of the bearing, the tolerance of the pillow block bore, and the tolerance of the shaft diameter.

Too much interference between the bearing and shaft can cause excessive friction and lead to premature wear on the shaft and the bearing load plates. Alternatively, too much clearance between bearing and shaft can result in fewer rolling balls being in contact with the raceway, leading to reduced load capacity and lower stiffness.



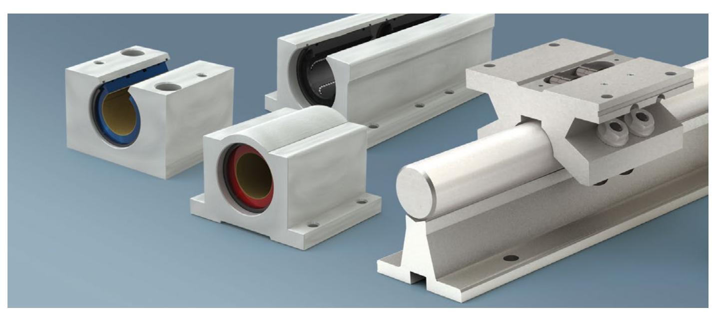
Adjustable pillow blocks allow the clearance between the bearing and the shaft to be reduced or eliminated.

Manufacturers provide guidance for the expected clearance between bearing and shaft when standard pillow blocks and shafts are used. However, if pillow blocks are manufactured in-house by an OEM or end user, it's important to follow the manufacturer's recommendation for the bore tolerance. Not only does this affect clearance between the bearing and the shaft, but too much interference between the inner bore of the pillow block and the outer bore of the bearing can also reduce bearing life.

Although too much interference can cause rough operation and reduced life, most linear ball bearings are able to operate with zero clearance or light preload between the bearing and the shaft. To achieve this, some linear bearings — and most pillow block designs — are available in adjustable versions, with a slot in the outer housing of the bearing or in the pillow block.

Adjustment of this slot — whether directly on the bearing or in the pillow block — slightly reduces the diameter of the bearing and removes clearance between the bearing inner diameter and the shaft outer diameter.

Round shaft pillow block options from PBC Linear.



MULTIPLE MEANINGS FOR *GOTHIC ARCH* IN THE WORLD OF LINEAR BEARINGS

Gothic arches originate from civil engineering. They're an adaptation of round-top Roman arches having a pointed shape resulting from the intersection of two circle-arch segments — called springing points when they're extensions of straight (and vertical) arch segments. In civil engineering, the benefits of Gothic arches are that they provide loftier arch reaches and half the (compromising) side thrust of Roman arches. In mechanical engineering, Gothic arches allow more clearance and greater roller to rail (or track) contact than other options.

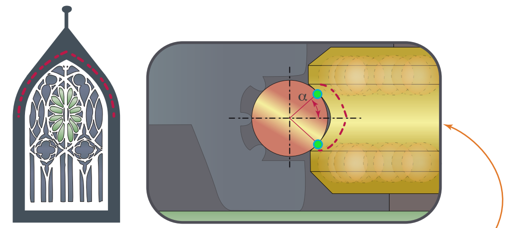
TRACK-ROLLER LINEAR GUIDE GOTHIC ARCHES

Gothic arches in the context of wheel-based track-roller linear guides refers to the roller wheel's outer working-surface shape — and the mating geometry of the linear track it rides. Gothic arch wheels have a highly engineered radial surface with a concave profile. That's in contrast with flat rollers, crowned (rounded) rollers, vee-shaped (notched) rollers, chamfered rollers, and flanged rollers. In Gothic-arch linear guides, the track is:

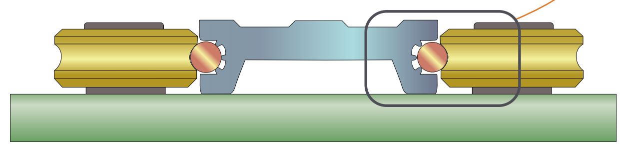
- A machined and treated surface on a section of standard rail
- A round hardened steel race embedded in a section of standard rail — with the latter often made of lightweight anodized aluminum.

When the ends of the build are obscured, these can visually resemble profiled-rail linear guides. Strength and straightness is to ±0.5 mm per 300 mm. The wheels' Gothic arch geometry ensures the wheels securely and smoothly ride these races … and many pre-engineered

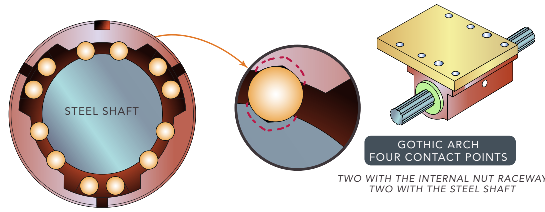
Raceway geometry affects axis stiffness, friction, and moment load capacity in both profiled rail linear guides as well as track-roller linear guides. In both linear guide types, Gothic arch geometry (on the raceway for profiled rail and on the track-roller OD for track rollers) provides four-point contact instances between the linear guide element and the rolling subcomponent. Gothic arch geometry can make for load capacities that are lower than other options, but also enables exceptional linear accuracy.



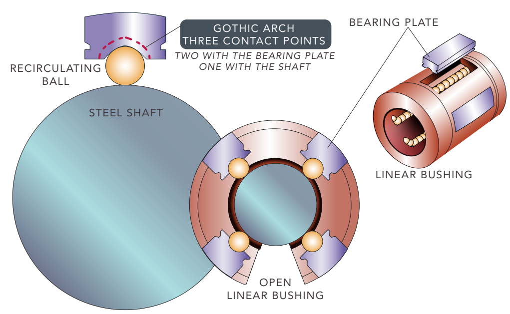
TRACK-ROLLER GOTHIC-ARCH CONTACT BETWEEN WHEELS AND RACEWAY



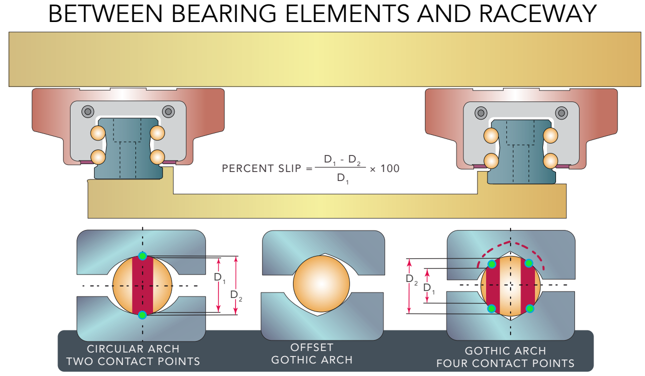
BALL-SPLINE GOTHIC-ARCH CONTACT BETWEEN BEARING ELEMENTS AND GROOVED SHAFT



LINEAR-BUSHING GOTHIC-ARCH CONTACT BETWEEN BEARING ELEMENTS AND ROUND SHAFT



PROFILED-RAIL GOTHIC-ARCH CONTACT BETWEEN BEARING ELEMENTS AND RACEWAY



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MULTIPLE MEANINGS FOR *GOTHIC ARCH* IN THE WORLD OF LINEAR BEARINGS

variations boost performance by integrating three, four, or even five gothic-arch rollers that are offset and trapped between the races of the linear track.

One final note: Track-roller wheels with Gothic-arch external profiles often contain double-row angular-contact ball bearings within. That allows them to bear the axial loads induced from both sides of their OD — as well as high radial forces with its *tread* — the wheels' thick OD working surface.

LINEAR-BUSHING LINEAR GUIDE GOTHIC ARCHES

Gothic arches in the context of linear bushings typically refers to the geometry of the raceways inside the ball-spline nut. Gothic arches in the nut raceways impart higher rigidity and lower backlash than nuts having other raceway shapes.

BALL-SPLINE LINEAR GUIDE GOTHIC ARCHES

Gothic arches in the context of ball-spline linear guides typically refers to the shape of the grooves along the long axis (or spiraling around) the ball-spline shaft … with the assumption that the assembly nut also has Gothic-arch geometry as described above for linear bushings. In fact, ball splines Gothic-arch groove geometries can often outperform those having grooves with circular (actually elongated elliptical) arch geometries. That's because Gothic arches ensure the ball bearings are contacted at four points — at two points on the nut raceway and two more points on the shaft groove. That's in contrast with circular geometry that only contacts each ball bearing at two points — at one point on the nut raceway and another on the shaft groove.

As with all uses of Gothic-arch bearing track, there's higher rigidity (as well as low or even no backlash) but more friction arising from heightened ball differential slip (skidding) due to the inclusion of more contact points.

Ball splines with shafts having circular-arch groove profiles excel on machine axes somewhat tolerant of slight backlash — namely those having low inertial moments and fairly consistent torque requirements. In contrast, ball splines with shafts having Gothic-arch groove profiles — which are often precision ground as described earlier in this Design Guide — excel on axes requiring dynamic torque transmission and rigidity.

Note: Though it's beyond the scope of this Design Guide, there do in fact exist ball splines that have custom-engineered shaft-groove geometries.

Popular Redi-Rail and Ball Bushings from PBC Linear are constructed with Gothic arch technology

PROFILED RAIL LINEAR GUIDE GOTHIC ARCHES

Gothic arches in the context of profiled rail linear guides are found in the geometry of the linear rail raceways — not the carriage or rolling elements. In fact, profiled-rail raceways usually have either circular-arch grooves or Gothic-arch grooves. These groove geometries (both of which are associated with guides employing ball-bearing elements) arose from industry innovation aimed at boosting linear-guide load capacities. Circular arch grooves contact ball bearings at two points. Gothic arch grooves contact the ball bearings at four points. Though beyond the scope of this Design Guide, a third option called an offset Gothic arch is also available.

Gothic arches in profiled rails offer multi-axis load bearing and high moment load capacities. Their main drawback is the tendency to fall out of pure rolling with differential slip resulting from speed-varying disparities in the elliptical contact areas between ball and raceway — as well as an increase in sliding friction. More dramatic differentials between ball and arch diameters (as well as increased contact area) makes for more differential slip. The relationship between this slip and contact area means the effect also puts a limitation on allowable preload.

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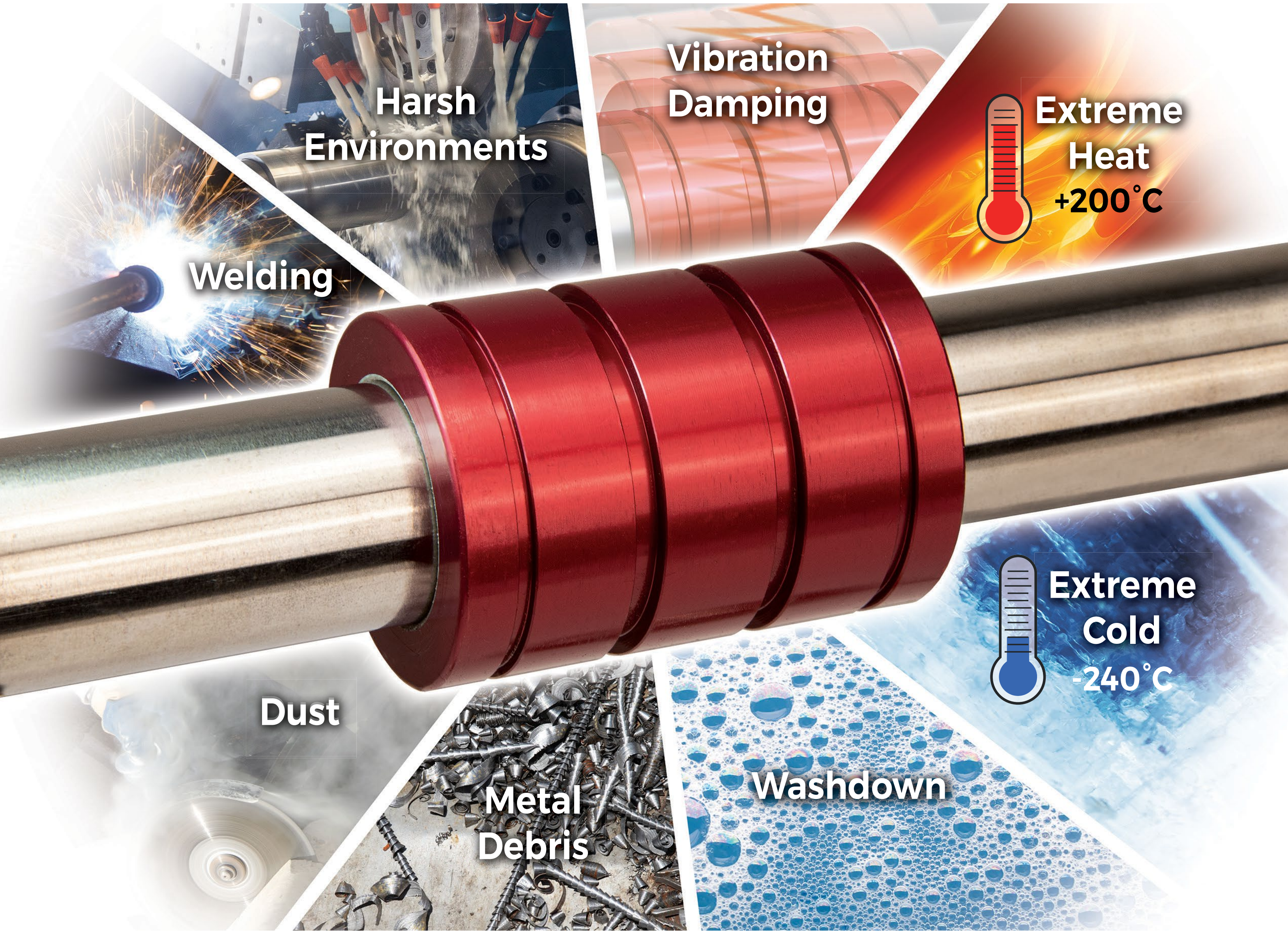

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