Selecting and Applying Rolling Element Linear Bearings and Guides

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Rolling element linear motion bearings are widely used to guide, support, locate, and accurately move machinery components and products in a wide range of automation applications. Rolling element linear bearings and guides provide low friction, smooth, accurate motion for nearly any moment or normal loading condition. Major applications include factory automation, medical, packaging, machine tool, semiconductor, printing, automotive assembly, aerospace and food processing.

Specifying the right bearing for a given application is necessary to save time and excessive costs. Understanding the tradeoffs of each bearing type is important to accurately size and select the right bearing for your application. Choosing an inadequate solution can lead to higher costs in design, surface preparation, materials, assembly, and bearing maintenance. Or worse, it can lead to insufficient machine accuracy, repeatability, and life, requiring an entirely new type of linear guide. This article will provide an overview of the major types of linear bearings and guides, explain how to specify them for specific applications and describe how to trouble-shoot common application problems.

Types of bearings and guides

Feature	Bronze Bushing	Air Bearing	Cam Follower	Round Rail Ball Bushing Bearing	Profile Rail Linear Guide
Load Capacity	**High**	Low	Low	Medium	**High**
Accuracy	Low	Medium	Medium	Medium	**Medium-High**
Smoothness	**High**	**High**	**High**	Medium	Medium
Ease of Installation	Medium	Low	**High**	**High**	Medium
Self Aligning	No	**Yes**	No	**Yes**	No
Speed	Low	**High**	**High**	Medium	Medium
Available Preloaded	**Yes**	No	Yes	No	**Yes**
Available End Support Mounting	**Yes**	**Yes**	No	**Yes**	No
Drag	High	**Low**	Medium	Medium	Medium

Figure 1: Comparative strengths of different bearing types

Designers have a wide range of bearing and guide alternatives for providing accurate linear motion. The chart above provides an overview of the advantages and disadvantages of the major types of plain contact sliding and re-circulating rolling element bearings. For example, the chart shows that bronze bushings have high load capacity and low accuracy while profile rail linear guides have high load capacity and medium accuracy.

This article will focus on linear rolling element bearings, which are represented in the two columns on the right of the chart, because they are used in most critical industrial applications. Linear rolling element bearings generate much less friction than sliding bearings so they require a much smaller motor and drive system and are capable of running at considerably higher speeds. Linear rolling bearings also eliminate the stick-slip effect that often causes chatter. They offer a predictable life and do not lose tolerance over their lives.

Figure 2: Round rail ball bushing bearing components (Super Ball Bushing bearing shown)

Round rail bearing system

The two major types of linear guides are round rail bushing bearings and profile rail bearings. A key advantage of round rail ball bushing bearing systems is their ability to accommodate torsional misalignment caused by inaccuracies in carriage or base machining or machine deflection with little increase in stress to the bearing components. The self-aligning-in-all-directions design of round rail bearings is forgiving of poor parallelism and variations in rail height. As a result, these bearings allow for smooth travel when mounted to wider-tolerance prepared surfaces.

In end-supported applications, the axis of motion of round rail guides is established entirely by fixing the two ends of the shaft. It doesn't matter what the surface of the machine is like between these two points or whether there is one at all. So round linear bearings are capable of spanning gaps up to 24 times the shaft diameter, making them useful in a range of applications such as pick-and-place modules and gantry systems. The accuracy of the guide depends only on the accuracy of the end-support mounting.

Traditional precision steel round rail bearings provide point contact on the inner and outer race so they are very low friction, and they offer a relatively lower load capacity. A more sophisticated design of round rail ball bushings offers a ball conforming groove on the outer race and maintains point contact on the inner race. This design offers a 3X increase in load capacity. An even more advanced design utilizes universal self-aligning dual tracks, offering a 6X increase in load capacity. This increase in load capacity is achieved by maximizing the load reaction between the inner and outer races. This break-through in load capacity rivals that of linear guides while still retaining the advantages of the round rail design that enable the linear bearing to avoid many of the derating factors that can diminish the load/life performance of square rail products.

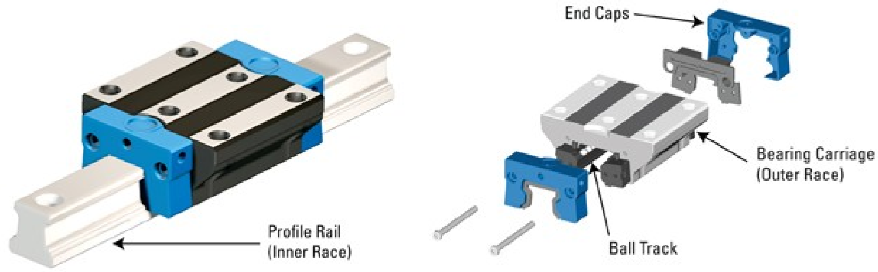

Figure 3: Profile rail bearing linear guide

Profile rail bearing systems

Profile or square rail systems offer higher accuracy, higher rigidity, higher load-life capacity, and are also very compact. Their key advantage is derived from ball conforming grooves on both inner and outer races that increases load capacity relative to standard round rail guides. The ball track groove in profile rail guides is only slightly larger in radii than that of the balls themselves. The geometry cradles the balls as they infinitesimally flatten under load, slightly expanding the contact area between the balls and the races. As a result, profile-rail bearings are roughly 10 times stiffer than a traditional round rail assembly with ball and shaft surfaces that are convex. Profile rail guides can provide positioning accuracy from 0.0002 inch to 0.001 inch over 10 feet. Square rails can be preloaded from 3% to 13% of rated dynamic load to further reduce deflection.

An aspect of concern for profile rail bearings are that mounting surfaces must be precise thus they are more difficult to install. Profile rail designs are especially sensitive to flatness errors that can cause binding. Surfaces must be carefully prepared or the parts may need to be shimmed and adjusted during installation. One common rail alignment method is to mount one rail on a qualified surface against one qualified reference edge, and float the second rail into place while moving the carriages. Three other alignment methods, in order of increasing complexity and accuracy, are to establish relative position of the rails by using gauges blocks, both reference edges, or a positioning laser.

An even higher rigidity or load-life capacity option is a linear Profile Rail roller guide bearing wherein cylindrical rollers run between flat races. Interestingly, there is also a Round Rail bearing using concavex rollers running on a cylindrical inner race that offer up to 20 times that load capacity of conventional linear ball bearings. Round Rail linear roller bearings handle up to 35 tons per bearing and speeds up to 100 feet per second. Their optimized contact ellipse maximizes the load capacity of an anti-friction linear bearing. Round Rail bearings can carry loads up to 70,000 lbs per bearing at a 10 million inch rated travel life.

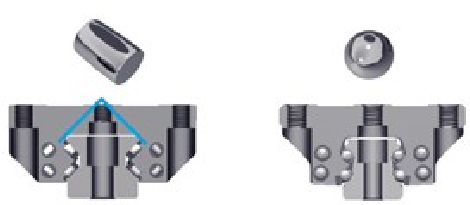

Figure 3b: Roller rail bearings offer increased load capacity over ball profile rail bearings as a result of increased contact surface. Machine builders can downsize from a typical ball profile rail assembly to a smaller roller assembly without compromising load capacity.

The Thomson 500 Series Roller Bearing Assembly achieves superior rigidity by use of 45° contact angles, a back-to-back arrangement and crowned rollers to prevent edge loading in case of any misalignment.

Advantages of the 500 Series Ball Bearing Assembly can include reduced stiffness, drag and simpler installation.

Selection of linear bearings and guides

The sizing and selection process is similar but not exactly the same for round and profile rail bearings. Loads acting on linear bearings and guides can be vertical loads, horizontal loads or pitch roll or yaw moment loads, or any combination thereof. Loads may also vary in their magnitude and direction. A resultant load vector at each bearing must be established from the combination of the various load vectors to which the linear bearing system is subjected, as life expectancy cannot be estimated based on just the system load vectors. The load under which each linear bearing is subjected is called the dynamic equivalent load for that given bearing. The system is then sized based on the most heavily loaded bearing. For more information on computation methods for a dynamic equivalent load, refer to the linear bearing and guide suppliers' catalogues.

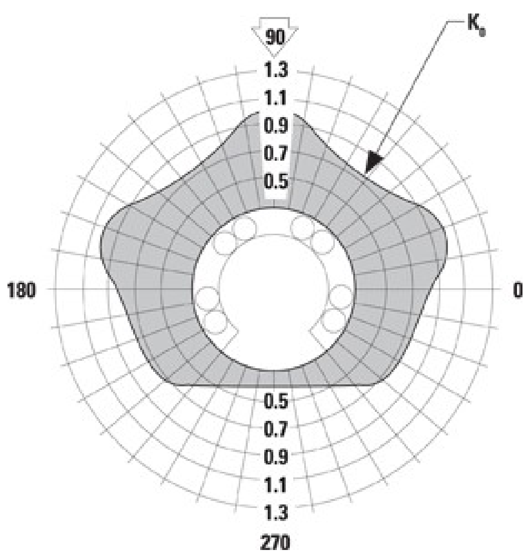

Figure 4: Determining effect of load direction

For a round rail bearing, the dynamic load rating is based on a load at top dead center. However, the actual bearing load capacity is dependent on the direction at which the load is applied. So a delimiter or direction factor must be applied to the rated load based on the actual polar direction at which the load is applied. Refer to the proper Polar chart for the product, similar to Figure 4, to determine the correct K_{θ}, direction factor. Find the angle at which the load is applied relative to the bearing, and move in radially along that line until it intersects the curve shown in Figure 4. Move around circumferentially to the polar correction values located on the vertical axis. Multiply the dynamic load capacity listed in the product specification table by the proper polar correction factor to adjust the load rating for load direction. You can perform a load-life calculation using the following formula:

$$L_m = \left(\frac{W}{P} \bullet K_\theta \bullet K_S\right)^3 \bullet L_U$$

L_m = travel life in inches or km
W = dynamic loading rating in lbs or N
P = applied equivalent load in lbs or N
K_θ = load direction factor
K_S = shaft hardness factor
L_U = 100 km or 2 X 10^6 inches

For Profile rail bearings and guides the equivalent loads to which the bearings are subjected are determined by the same method used for round rail bearings and guides. Load direction calculations, however, are not required because these bearings and guides have the same load capacity in all directions. The following formula is used for load/life calculations:

$$L_m = \left(\frac{W}{P}\right)^{n} \bullet 100km$$

Where: Lm = travel life (km)
W = dynamic load rating (lbs or N)
P = applied equivalent load (lbs or N)
N = 3 for all guides, 10/3 for roller guides

Two-rail systems are generally advised for most applications because more favorable load distributions between the bearings can be achieved, and self-alignment is possible with most Round Rail bearings. One-rail systems can be used in certain applications where envelope restrictions are tight. In these cases, profile rails are recommended to address pitch, yaw and roll moment load requirements. The use of three or more rails, or bearings per rail, is typically discouraged because of potential over-constraint, and equal load sharing between the bearings would be difficult to achieve. In addition, the use of three or more rails, or bearings per rail may shorten system life if they are not perfectly matched and aligned.

Linear bearing accuracy

Linear bearing accuracy is defined as the variation in height over the length of the travel. The best achievable accuracies for 120 inch rail length are +/- 0.0008 inch for round rail bearings and +/- 0.0001 inch for profile rails. In applications where running accuracy is critical, profile rail bearings typically can offer better accuracy than round rail bearings and metric round rail bearings offer better accuracy than inch round rail bearings. Super or ultra accuracy class profile rail bearings offer improved accuracy compared to standard profile rail bearings. Accuracy can also be improved by machining the mounting surface to a higher flatness tolerance and through the addition of a reference edge.

Bearing preload is used in both round and profile rail bearings to minimize deflection by removing any internal clearance in the bearing. This preload is provided by generating an interference fit between the outer race, rolling elements and inner race of the bearing. The heavier the preload that is created in the bearing, the less the initial carriage to rail deflection. Preload in a round rail bearing is typically achieved by adjusting or using an undersized housing bore or an oversized 60case shaft. Be careful not to over-preload the bearing as this could negatively affect the function of the bearing. Preload in a profile rail is set in the factory by using oversized rolling elements.

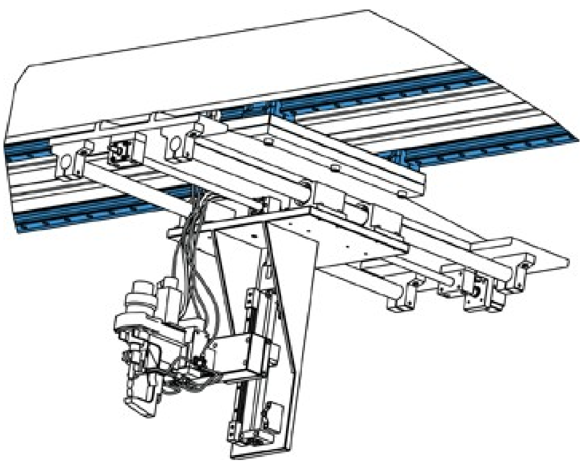
Figure 5: 3-axis linear guide application

Typical application

Let's look at how linear bearings and guides were selected for a typical application, a 3-axis welding gantry used in large-scale assembly operations shown in Figure 5. At a length of 5.8 meters, the x-axis is the longest axis and requires high load capacity and high stiffness because the welding head moving back and forth shifts the load from one rail to the other. Four 35 mm profile rail bearing cartridges were used to meet the load and stiffness requirements. Lifetime lubricated accessories were used because the carriages are difficult to access for maintenance.

The requirements for the Y-axis include gap spanning ability and medium load capacity. Profile rail bearings are not able to span gaps so round rail bearings were selected for this axis. A design with a ball conforming groove on both inner and outer races was used to meet load and life requirements. The Z axis requires a small footprint so a profile rail bearing cartridge with a high moment load capacity was chosen so that only one rail could be used. This approach is less expensive and less obtrusive than using a large rail or two rails and less expensive than using a wide rail.

Handling and lubrication

Bearings need to be carefully handled prior to proper installation. Shocks to the bearing can damage the bearing race or elements though brinelling or cracking. Shocks to the rail can lead to bending. Keep the bearings packaged and lubricated and stored in a clean, dry area because debris and contamination can jam recirculation tracks and high humidity or rain can cause corrosion.

Although there are some applications that have worked running bearings dry, lack of lubrication or lubrication breakdown is usually the main cause of bearing failure. Some users assume that the rust preventative oil the bearings are shipped in provides adequate lubrication for the life of the bearings. But proper lubrication is required for standard rolling element bearings to last, even under light loads. The bearings' catalog dynamic load capacities assume appropriate lubrication intervals. For low loads or higher speed low drag applications, a good machine oil may be sufficient. Oil flows more freely through the bearing, flushing out contaminants but also requiring more frequent re-lubrication.

Grease should be used for moderate to high load applications. The higher viscosity provides better adhesion. The channeling properties allow for less frequent lubrication.

For more demanding applications, lubricated-for-life accessories have a proprietary material that serves as an oil reservoir and outboard seals to protect the bearings from contaminants. The solid lubricant provides continuous lubrication for the life of the bearing. The minimum lubrication cycle is once a year or every 100 km, which ever comes first. More frequent lubrication may be required based on application specifics, like the duty cycle, usage, and environment.

Troubleshooting

Bearings should be inspected on a regular basis. A simple check of the shaft and rail can be done by running your finger along them. You should feel a thin film of lubricant. Re-lubricate the bearing if it is dry. Check the bearings, bearing outer race and shaft or rail for metal fragments. Shaft failure is common in short stroke applications where the stroke is less than 1.5 times the bearing length. Replacement of both the bearing and shafting may be required if metal fragments appear. Check the shaft for signs of wear such as spalling. Shaft grooving may sometimes be acceptable during the initial run-in if it is what is known as shakedown phenomena, and scratches are typically only cosmetic. Also, soft metal bearing housings, such as aluminum, can easily become indented at the bearing plate contacts. Indenting can interfere with bearing plate loading and self-aligning features so it may require the replacement of the housing.

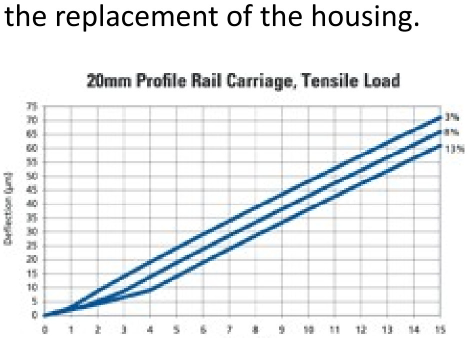

Figure 6: Load vs deflection at various preloads

Insufficient system repeatability problems are frequently caused by poor installation and set-up, excessive carriage deflection, or lack of stiffness. Stiffness can be improved by switching from round rail to profile rail or by switching from ball profile rail bearings to roller profile roller bearings. Repeatability can also be improved by reducing clearance in the bearing rail fitup. When profile rails are used, increasing preload will reduce deformation as shown in Figure 6. When round rails are used, an oversize shaft and/or undersized housing bore can be specified to reduce clearance or provide a preload.

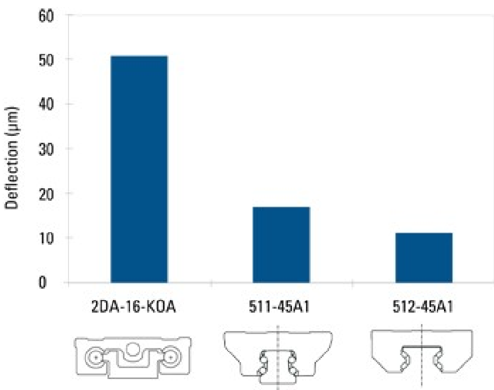

Figure 7: Carriage deflection under 12 kN (2700 lb) compressive load

Increasing bearing size will also reduce deflection or deformation and improve repeatability. Increasing the stiffness of the mounting surface can also improve repeatability. Figure 7 provides an example of the differences in deflection among three equivalent sized linear guides.

Bearing Types	Coefficient of Friction (µ)	Force to move 1000 lb
Bronze Bushings, no lube (typical)	0.300	300 lb
Bronze Bushings no lube best case	0.100	100 lb
Cam wheel on steel track	0.020	20 lb
Roller Bearing linear guide	0.007	7 lb
Typical Square Rail	0.004	4 lb
Best Ball Bushings (Instrument Grade)	0.001	1 lb

Figure 8: Bearing type vs. drag

The push force required to move a linear motion system can be reduced by lowering the bearing's frictional forces. Figure 8 shows the coefficient of friction of common linear bearing types and the corresponding force required to move 1000 pounds. To reduce push force, replace plain contact bearings with recirculating element bearings. To reduce excessive seal or wiper drag on profile rail bearings, replace a double lip seal with a single lip seal. For clean applications only, it may be possible to remove the seal/wiper entirely. Wear in the bearing or rail may also increase drag which can be corrected by replacing the worn parts.

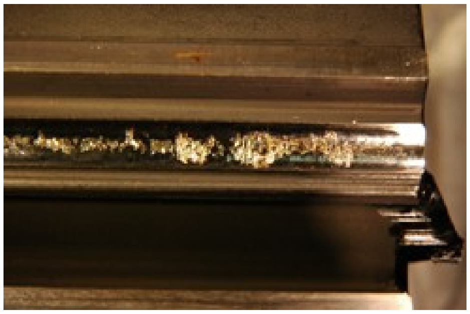
Figure 9: Profile rail bearing race spalling

Bearing race spalling as shown in Figure 9 can result in rough running, reduced accuracy and heat generation. One common cause of spalling is rolling contact fatigue of the bearing race or rolling elements. This can be addressed by replacing the bearing and rail. If insufficient life is achieved even with a new bearing and properly aligned rail, increase the bearing size. Another common cause of race spalling is insufficient lubrication or contaminant impingement. Lubricate the bearing before installation and establish a lubrication interval to help flush out the bearing.

The problem of ball bearings forcing themselves out of their retainers or end caps can have several possible causes. Check the straightness and parallelism of the rails and align the carriage and rails to the catalog specifications. If contamination build up is causing jamming of the ball tracks, add seals or wipers or scrapers or bellows. Other possible causes may be that high temperature, chemicals, radiation or excessive speed is weakening the plastic components. In this situation, use all-steel bearings.

When bearings or rolling elements crack in half and jam the bearing rolling element tracks, the cause may be shock loading or excessive static loads. Replace ball profile rails with roller rails for a 30% to 50% increase in load capacity. Replace standard length carriages with long carriages for a 20% to 60% increase in load capacity. If round rails are used, replace super type or conventional type bearings with bearings with dual tracks or ball conforming grooves on the outer races because they provide higher load capacity and travel life. Another possible cause may be excessive preloading due to two or more misaligned rails. Be sure to align the rails per the catalogue specifications for the product.

Excessive bearing noise can be caused either by insufficient or lack of lubrication or by steel balls hitting each other and the ball track. Try lubricating the bearing with an appropriate grease and establish a regular re-lubrication interval. Consider using round rail bearings with a Nylon ball or alternating Nylon-steel linear ball bearings. Another option is to consider composite-lined bushing bearings. Noise of profile rail bearings can also be reduced by using a 513 ball spacer carriage.

When a bearing system seizes up during activation, check to see if the rails and carriages are out of parallel. If so, re-align the rails and carriages per the catalog specifications. Also check the accuracy of the mounting surfaces or housing bore. If round rail bearings are used, replace with self-aligning bearings or with dual track self-aligning bearings. Machine the mounting surface and the housing to tighter tolerances may help. Another possible cause of a bearing system seizing may be incorrect bearing-shaft fitup. Check the shaft tolerance class and if necessary increase the bearing housing bore diameter to provide proper fit-up.

There are several possible causes of corrosion in linear bearing guides. If the guides are exposed to the elements, humidity, chemicals, or to liquids such as aqueous cutting fluids, try a corrosion-resistant linear bearing, a stainless steel or plated rail and properly lubricate both the bearing and the rail. If the linear guide is operating in a submerged environment, use a composite lined bushing bearing and 316 stainless steel shafting or use a specialty ceramic ball bushing bearing and shafting.

Linear bearing applications range from low precision such as sleds, carts and drawer slides, to medium precision such as saw guides, scanning, and door guides, all the way to high precision such as machine tools and metrology applications. In order to apply the correct type of linear guide in a particular application, the design engineer must consider the advantages and capabilities of each. Selecting the right technology can reduce design complexity, improve performance and reduce the overall cost of the assembly.