Ball Screw Fundamentals

An Online Continuing Education Course for Engineers

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Ball Screw Fundamentals

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Of all the systems used for linear motion control, it is the ball screw system that is increasingly becoming the method of choice for such motion control often replacing traditional systems such as pneumatic or hydraulic cylinders and Acme thread lead screws. This ever-increasing application of ball screws to linear motion control is due to their many advantages over these other systems. Among these advantages are their very high mechanical efficiencies of 90 percent or more and their ability to move heavy loads at high speeds and acceleration with outstanding accuracy. A ball screw – servo motor drive system can be a cost-effective alternative to pneumatic and hydraulic actuators since no compressor or hydraulic pressure supply unit is needed. Without ball screw technology, today's high-volume precision manufacturing would not be possible.

Modern applications of ball screws are extremely diverse and include replacing hydraulic actuators in aircraft control surface movement, high precision positioning in machine tools, robots and assembly equipment and automotive steering systems which were one of their first widespread commercial applications. In the 1940's the Saginaw division of General Motors introduced what was referred to as "re-circulating ball steering" in which the rotation of the steering wheel caused the linear motion on the steering shaft of a ball nut attached to a rack and pinion which rotated the parallel steering arms to move the tie rods left and right to turn the wheels. This was a marked improvement in automotive steering systems and was the basis for most automotive steering systems for decades.

The concept of the ball screw and nut assembly for reducing friction and operating clearance in motion control lead screws first appeared in "The Practical Engineer" publication of 9th and 16th December 1898 in an article entitled "The Design and Construction of Ball Bearings" by C.H. Benjamin. The illustration of his concept as printed in the article is shown here as Fig. 1

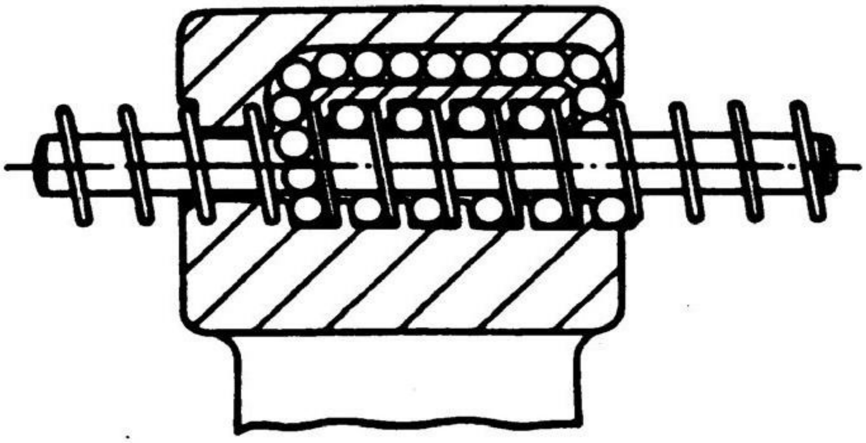

Fig. 1: A conceptual drawing of a re-circulating ball bearing screw system as presented in 1898

As is quite often the case, Mr. Benjamin’s idea was somewhat ahead of its time since it required precision spherical rolling elements that were consistently sized and available in large quantities at reasonable cost. After World War I ball bearings for rotating machinery started to become commonplace due to the introduction of the Conrad system for bearing construction and the development of processes for the manufacture of consistent, precision spherical rolling elements. In the time between the wars and during World War II, methods were developed to convert rotation to precision linear motion using conventional “V” thread or Acme thread systems by using a two-piece split nut and pre-loading the two nuts against or apart from each other. While these techniques did eliminate lost motion or backlash when reversing the threaded shaft and provided precise tracking of the nut driven machine elements with the threaded shaft, they increased friction and further limited shaft rotational speeds and the corresponding traversing velocity and acceleration of the controlled equipment. In the late 1950’s a great deal of interest developed in the Numerical Control of high end machine tools for precision, automated metalworking using punch cards or paper tape programs. These early systems relied on split lead nuts on V or Acme thread lead screws. As computer, drive and servo motor technologies advanced, the speed, acceleration and life limitations of these lead screw systems became unacceptable and the demand for the ball screw system as a substitute became intense.

Initially these pioneer NC machine tools were retrofitted with ball screw systems but soon thereafter companies such as Makino, Giddings and Lewis and Ingersoll began fitting their new models with them. The demand for precision and automation grew as computing and programming capabilities expanded rapidly in the 1980’s and by the end of that decade all major machine tool builders worldwide were producing Computerized Numerical Control machines with ball screw positioning on 3 or more axis’. An example of how ball lead screw systems are integrated into modern CNC machine tools can be seen in the construction of a horizontal spindle CNC milling machine as shown in figure 2.

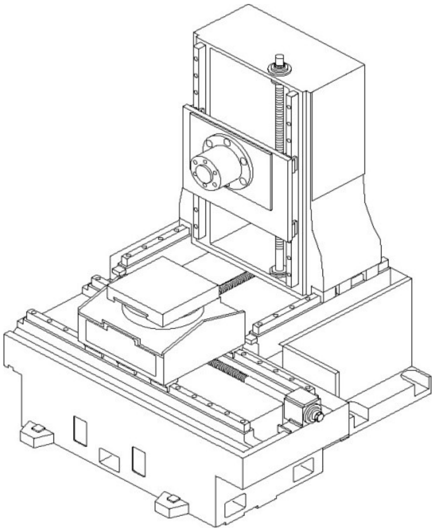

Figure 2: CNC milling machines' construction showing ball screw actuation of X – Y and Z axis

A ball screw shaft and its nut compare to an acme threaded lead screw in the same way that a pair of high precision, pre-loaded angular contact ball bearings compares with a plain bushing. Just as the bushing requires some clearance for the shaft to turn within it, the acme or V thread systems require clearance and this clearance results in lost motion when the shaft is reversed. Precise control of the positioning of the machine tool or robot can only be accomplished if the mechanical systems coupled with the servo-motor and encoder are capable of similar degrees of accuracy. Ball screws and their re-circulating ball bearing nuts are generally pre-loaded against each other to eliminate all lost motion or backlash. Unlike the angular contact ball bearing, the rolling elements of a ball nut travel in a continuous helical groove on the shaft and would fall out the ends if not arrested and deflected in the nut and redirected through a separate circuit or circuits which send them back to their point of origin and are thus re-circulated. The basic concept of this recirculation and ball screw system operation is shown in figure 3.

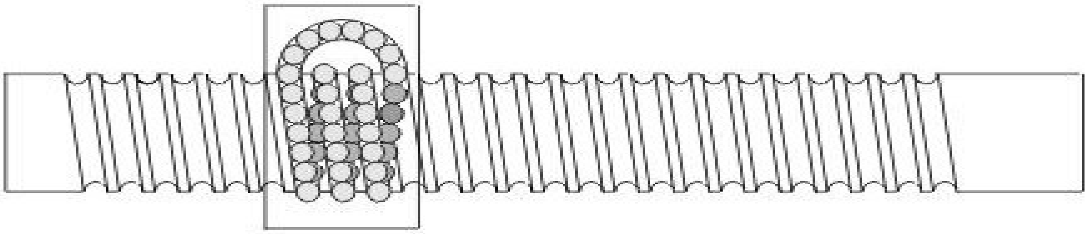

Figure 3: Ball screw assembly showing approximately 2.5 threads fully engaged with bearings and others in the re-circulation circuit (shaded balls are in positions behind screw shaft)

Ball screw shafts and rolling elements are made from the same general case hardening alloys of steel as ball bearings and are similarly case hardened to a minimum hardness of 56 Rockwell C, stainless steel ball screws are also available for special applications. Stainless steel ball screws have substantially less load capacity than the more common case-hardened steel grades because the stainless alloys available can be precipitation hardened to an upper limit of approximately 40 Rockwell C. Ball screw shafts are produced using one of three common procedures with the least expensive screws being finished as rolled by passing the shaft through rotating dies to deform the round shaft and generate a helical thread pattern. Since rolled screws can have error in the lead (the linear distance traveled by the nut or screw during one full rotation) accumulation of over .003” per foot, they are used for applications such as grippers or part shuttles where motion must come to a consistent point but intermediate accuracy is less necessary, screws finished by rolling are also noisier in operation due to the surface finish of the rolled helix, these types are unsuitable for precision machine tools or lithography equipment, rolled screws also have substantially lower rotational speed limits due to this surface finish. By far the most common ball screws used in precision applications such as machine tools and robots are produced by a combination of rolling the shaft helix to near net shape and then finished by grinding the shaft after case hardening. The third process used in producing the ball screw shaft eliminates the rolling operation completely and rough grinds the helix in the shaft prior to case hardening and subsequent finish grinding. Screws produced by this method are the costliest and are generally only specified in safety critical applications such as aircraft control surface actuators because this method eliminates the possibility of stress concentration in the shaft caused by the material deformation during a rolling operation.

The accuracy of a ball screw system involves several factors, and some are often overlooked when specifying a system. The most common parameter used when comparing system accuracy is the lead error of the assembly however other factors can be of equal or even greater significance in how they can affect the performance of your design. These sometimes-overlooked criteria of a ball screw-nut assembly include: the screw shaft straightness, the bearing journal concentricity with the helix, the torque resistance consistency of the shaft through the nut over the length of the thread and the accuracy in perpendicularity of the nut mounting provision (flange) to the shaft. More recently, standards such as DIN/ISO and JIS have included these parameters in their grade rating of ball screws but the allowed values must be considered when determining the grade level required by your application. Ball screws are highly intolerant of side loading and their life will be decreased by up to 90% if an excessive side load, eccentric load or moment is applied to them and therefore it is useless to specify a high quality or grade of screw assembly if the mounting of the nut in its retaining bracket cannot be carefully controlled. As a rule, the location of the center line of the nut when installed into your application must be within .0008” of the center line of the shaft. Likewise, the axial center of the nut must be kept within .0005” per inch of nut length of parallelism to the shaft axial center to avoid excessive side loading or moments.

As defined earlier, the Lead of a screw is the linear distance traveled by the nut or screw during one full revolution and the lead error is the deviation from the theoretical lead. A ball screw with an accuracy grade of 5 per the DIN/ISO standard is allowed a maximum lead deviation of 23 microns per 300 mm or about .0009” per foot. Under this standard, lead deviation is not cumulative and a screw three times as long (900 mm) is allowed 40 microns or less than twice the error. Ball screws are available in standard grades that are allowed less than 25% the lead deviation as the grade 5 example. If the ball screw error is known and consistent this error can sometimes be accounted for in the machines controlling software in the form of “lead screw compensation” to make the machines’ motion accurate and predictable.

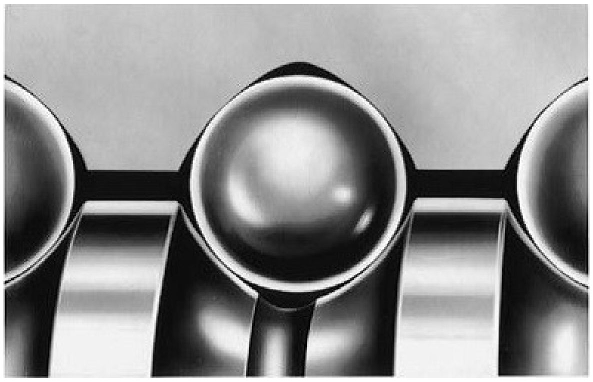

Figure 4

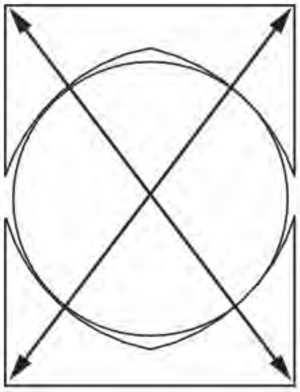

Figure 5

Regardless of how the helical shapes on the shaft and in the nut are produced, the desired outcome of the groove profile in cross section takes the form of a Gothic Arch as can be seen in figure 4. This is done so that the contact areas between the rolling elements and the shaft and nut can be carefully controlled to have a known and consistent thrust application angle during operation and when pre-loading the nut on the shaft, figure 5. This geometry is what allows ball screw assemblies to operate freely when pre-loaded sufficiently to eliminate all lost motion when reversing the shaft and to hold the load in place against an opposing force as is developed in a machine tool or aircraft control surface application when the driving servo motor is given a zero speed or stop command.

Although some ball screw assemblies are intentionally produced without any preload, most assemblies are made with some amount of preload ranging from extra light to heavy with
several degrees in between. In this way they are again ver cision angular contact
bearings which are generally applied i eliminate axial end
play in shafts and transr ary housing. Unlike
angular contact thrust b r the degree of
preload by varying the th outer races of the
bearings, the level of pre factory in most cases
and cannot be changed by for the Engineer to
be confident in the amour nt preload being the
most common in industria a ball screw system
by taking advantage of a pl e deflection of the
nut responds in a linear fas n the load-
deflection curve. At this poi ses to a much
lesser degree than the appli curve that the
preloaded ball screws are in

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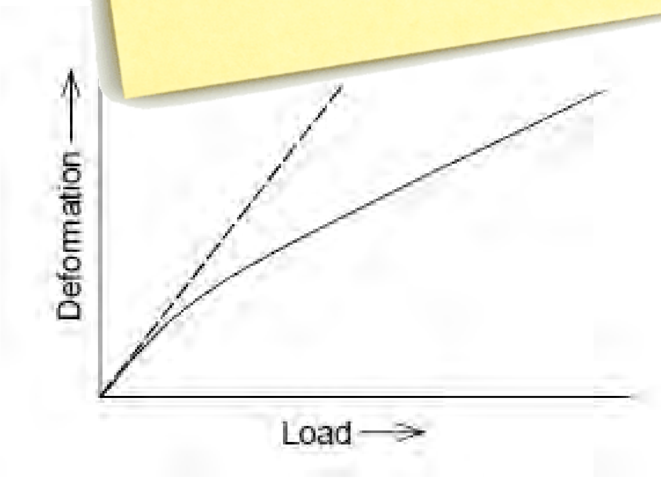

Figure 6: The divergence area in the load – deformation curve in which preloaded ball screws operate. The inflection point, or knee, is where the solid (deformation) line separates from the dashed (applied load) line.