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Alexander H. Slocum

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an error in the calculated velocity if it is assumed that the damping is constant. This error is on the order of parts per billion and thus may be insignificant; however, the error may become important if the friction drive is used on a machine where slow contouring cuts are made and nanometer accuracy is desired. In this case, a digital control algorithm with good filters may be needed to determine higher order derivatives (e.g., acceleration and jerk) which would allow for very accurate velocity control in the presence of the nonlinearities caused by nanoslip. It may even be necessary to make the control coefficients functions of the velocity.

10.8.3 Leadscrews

The principle of a leadscrew and nut has been used for centuries to provide a means for converting rotary motion into linear motion. By turning a leadscrew and holding a nut so that it does not rotate, the nut moves along the length of the leadscrew. Alternatively, the shaft can be held and the nut turned. This provides an effective means for attaining linear motion that has been used in countless machines. The introduction and the continued success of the leadscrew is due to the fundamental fact that rotary motion motors are easier to produce and are often more efficient than linear motion motors.

The first known application of a screw thread to do useful work was perhaps Archimedes' screw pump, which converted rotary power of a screw into an elevator for raising water from a river to an irrigation ditch. The first leadscrew cutting lathes were introduced in the fifteenth century and were used to manufacture wooden screws. Wooden screws led to metal screws. Screwthreads could be increased in accuracy with hand finishing and it was just a matter of time before they developed into useful tools for metalworking.

It was found that even though leadscrews were prone to manufacturing errors, the effect of many threads in a nut that was made somewhat compliant (e.g., leather threads), and forced to engage the leadscrew simultaneously, caused some of the errors to average out. Thus, by snugly fitting a nut to a leadscrew and wearing it in, the accuracy to which leadscrews could be manufactured steadily increased. Each more accurate screw was used to make an even more accurate screw. As early as 1800, Henry Maudslay was credited with developing a leadscrew with four threads per millimeter and an accuracy of 25 μm. In 1855, Joseph Whitworth developed a leadscrew-driven machine that could compare differences in the size of parts to within 1 μin. Eventually averaging reached its limits, and elaborate mechanical corrector cams evolved to correct lead errors. Fortunately, with modern sensor and servo systems, corrector cam mechanisms are a thing of the past.

In the remainder of this section, the basic physics of operation common to most leadscrews will be discussed in detail. The results shed insight to the operating properties of perhaps the most common actuators in use today on precision machine tools. With these results one can determine not only the drive torque, but the efficiency and the magnitude of "noise" moments created in the leadscrew nut, which can cause small pitch and yaw errors in a leadscrew-driven carriage.

There are many types of leadscrews that are available including:

- Sliding contact thread leadscrews
- Traction-drive leadscrews
- Oscillatory motion leadscrews
- Nonrecirculating rolling element leadscrews
- Planetary roller leadscrews
- Ballscrews
- Hydrostatic leadscrews

10.8.3.1 Leadscrew Operating Principles

A leadscrew is one of the simplest and best known power transmission elements. In this section the following will be discussed:

- Error sources
- Force and moment analysis
- Backdriveability
- Efficiency
- Noise moments

Where applicable, later in the discussion of specific types of leadscrews additional comments will be made. Note that the stiffness is dependent on the type of thread interface (e.g., rolling or sliding) and is discussed in the context of each type of leadscrew.

All leadscrews may be subject to many different types of error sources, including[92]:

1. Lack of squareness between the thrust collar and the thrust bearing will produce a periodic error in the system.
2. Eccentricity of the support journals and the screw shaft will cause periodic errors. Unless the nut is correctly coupled to the carriage, journal eccentricity will also cause straightness and angular errors in the carriage motion.
3. Lateral and angular misalignment between the screw and nut, and nut and carriage causes straightness and angular errors in the carriage motion as well as small periodic errors. In addition, the straightness of the leadscrew shaft and the amount it bends under its own weight will affect carriage motion accuracy.[93]
4. A varying pitch diameter will cause periodic errors and can contribute to backlash.
5. Mating thread form profile errors will cause periodic errors, backlash, and limit resolution.
6. Thread form errors (drunkenness) cause periodic errors. In the case of a multistart thread, which is used to increase the load capacity but does not change the transmission ratio, the relation between the threads' relative angular orientation also causes periodic errors.
7. Journal support bearings can be sources of periodic error, lateral motion, and backlash.

The net result of many of these types of error sources can be seen in Figure 6.4.6. Periodic errors can readily be mapped or obviated through the use of linear position sensors. Resolution can be increased by polishing components. Backlash, however, continues to be a difficult problem to deal with. One of the most common methods for dealing with backlash is to use two nuts that are preloaded against each other. With sliding contact acme threads, the nut can be split and circumferentially clamped so that the threads are wedged into each other. With ballscrews, oversized balls can be used, but this leads to increased rolling friction, because the groove shape is a Gothic arch and four-point contact results. With care all errors can be dealt with; the task is to identify the source of error. In addition, as discussed below, in generating an axial force, a leadscrew also generates moments about axes orthogonal to the shaft, thereby creating other forms of error. When selecting a leadscrew and incorporating it into the design of a precision machine, one must be very careful to consider all of these effects. *Caveat emptor!*

Force and Moment Analysis[94]

The mechanical advantage provided by a leadscrew is a function of the lead and efficiency. The lead ℓ of a leadscrew thread is defined as the linear distance the nut travels in one revolution of the nut relative to the shaft. For a rotation angle ϕ (in radians), the distance x traveled is

$$x = \frac{\ell\phi}{2\pi} \qquad (10.8.1)$$

The lead angle θ is found by unwrapping a single turn of the thread which rises a distance equal to the lead ℓ, at a pitch radius R:

$$\theta = \tan^{-1}\left(\frac{\ell}{2\pi R}\right) \qquad (10.8.2)$$

It is assumed here that the thread depth is small compared to the pitch radius, so the lead angle is essentially constant. For deep thread screws, θ is a function of R and the analysis becomes more complicated, but of the same form, as follows.

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[92] Remember, choosing a component is like farming. No matter how good the component (or crop), it will always be subject to various types of bugs.

[93] See Section 2.5 for a detailed discussion of the effects of forced geometric congruence.

[94] *"Mathematics is the alphabet with which God has written the universe."* Galileo Galilei

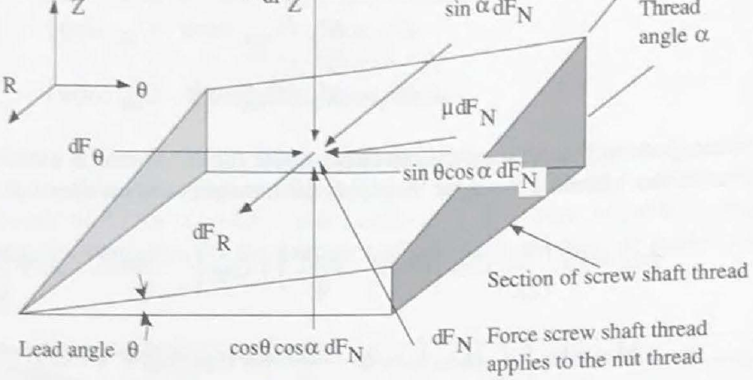

Figure 10.8.7 Forces a section of leadscrew thread apply to the nut thread when lifting (working against) a load. The thread normal force has been decomposed into its components.

Figure 10.8.7 shows a section of a leadscrew thread that is being used to lift (work against) a load. The relation between the differential axial force dF_Z and the differential circumferential and radial forces are found from a summation of the forces at a point:

$$dF_\theta = dF_Z \left\{ \frac{\ell\cos\alpha + 2\pi R\mu}{2\pi R\cos\alpha - \mu\ell} \right\} \tag{10.8.3}$$

$$dF_R = \frac{-\,dF_Z \sin\alpha}{\cos\alpha\cos\theta - \mu\sin\theta} \tag{10.8.4}$$

For the case where the screw is used to lower a load

$$dF_\theta = dF_Z \left\{ \frac{2\pi R\mu - \ell\cos\alpha}{2\pi R\cos\alpha + \mu\ell} \right\} \tag{10.8.5}$$

$$dF_R = \frac{-\,dF_Z \sin\alpha}{\cos\alpha\cos\theta + \mu\sin\theta} \tag{10.8.6}$$

The presence of the radial force is a hint that one must look at what else is happening to the nut in addition to the usual calculation for the required drive torque.

Since the depth of thread is assumed small compared to the diameter of the screw, the axial force can be considered to be distributed around a helical line through a thread contact angle Ψ. The differential axial force dF_Z is thus

$$dF_Z = \frac{F_Z\, d\psi}{\Psi} \tag{10.8.7}$$

For a right-hand coordinate system superimposed at the center of the leadscrew shaft, the Cartesian coordinates of any point on the helix at an angle ψ will be

$$X = R\cos\psi \qquad Y = R\sin\psi \qquad Z = \frac{\psi\ell}{2\pi} \tag{10.8.8}$$

We are interested in the case where gravity does not help the leadscrew to move the load (i.e., *raising* a load versus *lowering* a load). For convenience, let the following constants be introduced:

$$C_{\theta R} = \frac{\ell\cos\alpha + 2\pi R\mu}{2\pi R\cos\alpha - \mu\ell} \qquad C_{RR} = \frac{-\sin\alpha}{\cos\alpha\cos\theta - \mu\sin\theta} \tag{10.8.9}$$

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