DOVER MOTION
A division of Invetech

159 Swanson Rd.
Boxborough, MA 01719
Phone +1.508.475.3400
dovermotion.com

Limitations of Leadscrews

By Kevin McCarthy, Chief Technology Officer

Leadscrews are an effective means of translating rotation into linear motion, and provide a popular and cost effective actuator for many positioning stages. At Dover Motion, we ship thousands of screw-driven axes each year, and are very well aware of their strengths and weaknesses. For many applications, leadscrews remain the actuation technology of choice. Their intrinsic mechanical advantage is often of value; this allows them to support gravitational loads without a counterbalance, as well as to generate significant axial force. Common variants of leadscrews include rolled, ground, and lapped threads, and their mating nuts can be provided in anti-backlash friction-nut form, ballnut, and planetary configurations. There are also “threadless” nuts, which employ angled radial bearings on a plain shaft. A recent innovation for stepper-based stages is the integration of the leadscrew and nut assembly with the rotor of the stepping motor; in these products, the motor bearings replace the traditional duplex bearing pair at the end of the leadscrew, and a flexible coupling is no longer required.

Despite the effectiveness of leadscrews in general purpose positioning systems, they begin to run out of steam as the required resolution increases. All leadscrews suffer from some basic performance limitations. These include:

- Both cumulative (long period) and periodic (once per revolution) errors
- Motion-induced heating and subsequent thermal expansion
- An axial resonance set by the payload mass and the nut/screw column/bearing stiffness
- A trade-off between speed and resolution
- Wear and preload variation over time
- Variable friction torque, including (in ballscrews) torque transients due to balls entering and leaving the preload zone, as well as ball stacking.

The axial resonance directly degrades settling time for open loop stepper or rotary encoded servo systems, and indirectly degrades settling time for linearly encoded systems, by lowering the achievable servo bandwidth. Settling time is important in field-sequential imaging and focusing, where the ability to make many small moves per second and settle to a tight tolerance is directly tied to throughput. In friction nuts, the axial resonance is typically low in frequency, but fairly well damped. In ballscrews, the axial resonance occurs at a higher frequency, but is typically quite high in Q, and can take a while to ring down. In addition to the deleterious effects of the axial resonance described above, the friction torque of the nut and duplex bearing creates a dependence on the use of the servo loop integrator term, which lengthens the settling time. Periodic (once per revolution) error and torque transients in ballscrews render them inferior in the constant velocity motion required by scanning imaging applications. Leadscrew-based stages are very crude in precision touch-off applications, where the force goes from zero to “broken” in a few counts. The cleanroom compatibility of a rapidly spinning, lubricated leadscrew is also less than ideal.

Generally speaking, the axial thermal expansion and common levels of periodic error (2 – 10 microns) found in most leadscrews restrict their use in open loop or rotary encoded applications to resolutions of about 1 micron or higher. Any well-preloaded leadscrew will have a definite friction torque, and the energy deposited in the leadscrew when it rotates is simply this torque (in Newton-meters) times the number of radians of rotation. In high-resolution applications, this thermal expansion can be easily seen after each move, where it manifests itself as a slow creeping after each move ends. Attempts to reduce jitter and creep by disabling motor current after a move often backfire, as the motor rotor will often slowly creep towards its poles, even in a brushless three-phase motor.

Investment in a linear encoder improves the system precision, but the nut and duplex bearing are now within a feedback loop; this rules out most compliant anti-backlash nuts. Inclusion of the mechanics of the leadscrew and its related hardware within a linear feedback servo loop amplifies many of the system weaknesses. Leadscrews (typically ballscrews or lapped metal friction nuts) used in this manner must be stiff enough to provide a sufficiently high axial resonance, but the resulting friction increases the dependence on a sluggish integrator term, and the high Q of the axial resonance complicates closing a high-bandwidth servo loop.

Friction torque would be bad enough if it were constant, but inevitably it varies, both once per revolution and along the travel. Ballscrews also exhibit momentary torque spikes due to balls entering and exiting the preload zone, as well as from ball stacking. Then there is the whole issue of lubricants, their periodic replenishment, gumming up, and other perversities of the viscous interface. In a nutshell, all contact is corruption, and the multiple elements of mechanical “claptrap” in a leadscrew based system make efforts to extend resolution down to 100 nanometers and below a losing proposition. It can be done, but it isn’t pretty. The result, if achievable at all, usually requires a high-strung, heavily tweaked (often on a per-axis basis) match between servo controller and stage, with sluggish move and settle times, low throughput, and borderline stability. “Hmm… it’s buzzing again at the far end of travel; try lowering the gains and see if that stops it”. We don’t need this.

Leadscrew based stages can be contrasted with non-contact, direct drive technology, whose motion capabilities are limited only by encoder resolution (now easily available at and below the 1 nm. level), very precise PWM and linear servo amplifiers, and background vibration levels. Depending on the choice of encoder and servo electronics, clean staircase moves of as small as 10 nanometers in individual step size can be reliably delivered.

Precision optical applications frequently benefit from as much “real” resolution as they can get, and replacing leadscrew based systems with non-contact direct drive technology is the best way to achieve this. The comparison between a marginally tuned, sluggish leadscrew based system that is struggling to get below 100 nm. resolution, and a direct drive, crossed roller or air bearing stage, with a precision servo amp, and an encoder resolution in the nanometer range, can be dramatic. The gain in throughput alone can be as large as a factor of ten. While direct-drive systems have a reputation for being premium-priced solutions, Dover Motion’s innovations in motor and encoder design, together with our compact, precise, and cost-effective servo controllers, can make this premium shrink dramatically, and even reverse sign. Reach out to our application engineers, and challenge them with your system requirements!
