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Basics of Linear Drives

Synopsis: This paper examines how rack and pinion drives compare to linear motors and ball screws. Four key areas are examined: Linear Motion, Ball Screws, Backlash and Electronic Pre-Loading and Inertia.

Linear motors, ball screws, and rack-and-pinion drives are all good options for engineers designing electro-mechanical linear motion systems. Ball screws enjoy widespread use, and linear motors are noted for precision and dynamic performance. But with advances in precision manufacturing and the recent advent of electronic preloading, the accuracy and performance of rack-and-pinion drives can match or exceed that offered by competing hardware. And rack-and-pinion units often top the others in terms of durability, efficiency, and economics. Here's a look at how these drives compare.

Linear Motors

Linear motors became popular in the 1980s and many innovative products have been introduced over the last several decades. A prime benefit is the moving carriages of linear motors typically have low mass, permitting high acceleration rates and peak speeds. They're also suited for applications that demand high positioning accuracy or where motion frequently changes direction. Brushless linear motors run quietly and the drives typically have long lives.

On the downside, they have limited force capabilities and, despite improvements, are still rather inefficient—energy consumption is up to five times that of similarly rated rack-and-pinion actuators. Higher energy demands may mean larger up-front infrastructure investments for high power lines, transformers, and electrical drives. And linear motors generate a lot of heat and often need a secondary cooling system, which adds cost and complexity and further hurts overall efficiency. Heat generation can be extreme in low speed, high-force operations, such as drilling. These applications also require very stiff machine frameworks to resist compliance that can be caused by the strong magnetic fields of a large linear motor.

Because they are direct drive, linear motors cannot take advantage of gear reduction. Gearboxes are commonly used to match a rotary motor's speed and torque to the load. With a linear motor, that's not possible and it sometimes leads to a less efficient system.

From a closed-loop control standpoint, external loads that induce position deviations can cause oscillations or resonances. Without the reduction in inertia and damping inherent in a mechanical system, controls issues may surface at the workpiece.

Among other considerations, contamination from metal chips, particles, and even small parts can be a problem due to strong magnetic attraction if the linear motor isn't protected—although contamination can adversely affect other drives as well.

Rack-and-pinion drives can match or exceed the performance and accuracy of other electromechanical motion systems, and are more efficient.

And with rack-and-pinion's and ball screw's, brakes can be built-in to the back of standard servomotors. Linear motors, on the other hand require an add-on secondary brake that's typically more expensive.

Linear motors are generally cost prohibitive for long travel lengths. And even with shorter travel requirements, engineers should weigh a linear motor's potentially higher cost and energy use against performance advantages and machine productivity. In some cases, for instance, linear motors cannot reach top speed if acceleration and deceleration distances exceed the total travel distance. This can make the linear motor's technical advantages a moot point.

Ball Screws

Ball and leadscrews have been used for years in all types of industrial applications. Among their advantages over other linear drives, ball screws are economical for short travel lengths, so they're often preferred for applications such as Z-axis drives. And leadscrews and high-lead ball screws can be non-back drivable—meaning a vertical-axis load will lock in place and not fall if power fails.

On the downside, ball screws act as large springs sensitive to jerk (change in acceleration) and to impact loads that can cause damage and harm performance. The design also limits acceleration and deceleration capabilities and maximum speed and output force.

Maximum length is another limitation. Ball screws mount to a structure at both ends, as there is really no good support mechanism anywhere else. So as travel length increases, unsupported length grows, the screw sags, and performance suffers. Maximum axis length is typically around 6 m.

And a screw's linear stiffness is not constant but depends on nut position, which can create headaches in dynamic applications. Eliminating lost motion or backlash in ball screws usually requires preloading, incurring more friction, power loss, and potential for abrasion.

By design, a ball screw has a series of ball bearings that travel and recirculate through the nut and screw, lubricating the balls and evenly distributing load, friction, and wear. However, this can make screws noisy. And short-stroke applications prevent complete recirculation of the balls. In such cases, dynamic loads must be derated.

Rack-and-Pinion

Rack-and-pinion systems convert rotary motion to linear motion. A pinion engages a geared rack which moves the pinion and gearbox back and forth along the rack as the pinion rotates.

Advantages include unlimited travel length, and backlash free operation in dual drive systems with electronic preloading. In fact, a significant benefit over other designs is lower costs over long travel length. Travel is only limited by the length of the rack, and rack sections can be linked together end-to-end to increase travel length.

Pinions can be selected in various types and sizes. Helical gearing lets teeth engage smoothly and quietly. The smooth engagement of helical teeth allow for better part quality and surface finish when used in machining applications. Smooth running also helps ensure good part quality and surface finish, for example, when machining tight-tolerance parts. For high-precision systems, single-pitch error between helical teeth can be around 3 μm, and cumulative pitch error only 12 μm/500 mm.

Rack-and-pinion actuators have high force capacity, and they are capable of high acceleration rates and peak speeds—often nearly as high as those of linear motors. In many cases, the frame and structure—not the actuator—limit peak speeds in rack-and-pinion and linear-motion systems. Ball screws cannot accelerate like rack-and-pinion sets, nor can they maintain the same speeds. Their stiffness is lower and less constant. Rack-and-pinion units have lower mass moments of inertia and higher natural frequency and efficiency over ball screws.

Rather than connecting rack-and-pinion drives directly to workpieces, mechanical-transmission elements let engineers vary gear ratios and pinion size, and add damping that can eliminate closed-loop instabilities. In essence, it gives designers an extra element to tune the system and improve performance and efficiency.

Rack-and-pinion drives boast efficiencies as high as 97%. In comparison, linear motors generally have overall efficiencies of 85%, though some are considerably lower. Ball screws, depending on whether or not preloaded, can have efficiencies up to 90%.

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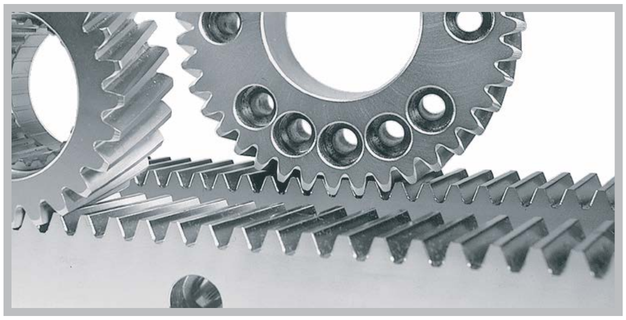


On the downside, the rack must be kept clean and lubricated, and the lube can splash at high speeds. They have fewer components than ball-screw systems which can save time during installation. But in high-precision applications have installation procedures that require close attention to detail, and the components can be expensive.

Typical rack-and-pinion applications include gantry, transport, and packaging machines that carry from a few pounds to several tons. Next generation rack-and-pinion sets are also used in woodworking, high-speed metal cutting, and assembly machines.

Backlash & Electronic Preloading

One consideration with any geared system is backlash. Backlash is the amount of clearance between gear teeth, typically measured in arc-min. All gear sets require some clearance. Without it, problems like tooth scoring and high bearing forces arise.

To minimize backlash, gears need to have high internal stiffness (material strength), be made with tight manufacturing tolerances, and use the right lubricant. Sometimes, rack-and-pinion sets are preloaded to eliminate backlash and increase stiffness. More-sophisticated rack-and-pinion sets take advantage of recent advancements in electronic preloading. These actuators have a single rack with two pinions and two motors, working in tandem, along with an electronic controller. They give backlash-free motion while minimizing frictional losses, making them more precise and energy efficient than conventional rack-and-pinion units.

Here's how it works. Master and slave pinions–both actively powered - push on rack teeth facing in opposite directions. At standstill, they generate opposing torque and the restraint, or electronic preload, is at its maximum. This eliminates backlash or "play" in the system.

The controller reduces electronic preload during acceleration. The master pinion initiates motion while the slave pinion eases the opposing force preload. As the unit accelerates, the slave transitions to the opposite tooth flank and both actuators act in tandem, but still without backlash. This is important because traditional preloading does not let both axes work together. Instead, one pinion always pushes against the other, creating inefficiencies.

During constant-speed movements, electronic preloading is disabled and both axes work together to carry the load. Inertia and workpiece resistance maintain backlash-free operation. Finally, during deceleration, the slave pinion again transitions to the opposite tooth flank, increasing restraint to help slow the load and eliminate backlash. There is no backlash during load changes because the tooth and flanks never lose contact.

Rack-and-pinion linear actuators with electronic preloading are intended for high-end applications that demand accuracy and rigidity despite highly dynamic motion. Examples include high-speed cutting equipment, robot motion platforms, portal milling machines, profile machining centers, and laser cutting machines.

Selection & Sizing

When selecting a rack-and-pinion system, engineers must consider a number of parameters, such as: the mass to be moved; motion orientation; acceleration rate and maximum linear speed; motion profile and duty cycle; and repeatability and accuracy requirements. Finally, how demanding is the environment, and how long is the system expected to last?

With all the variables, choosing the right rack-and-pinion design can be time consuming and costly. Searching through the catalogs and web sites of gear reducer and motor manufacturers, and making calculations for various combinations, is tedious and error prone. Fortunately, some major manufacturers of precision gears offer software tools to ease the task. For example, Cymex 5 simulation software from Wittenstein Inc., Bartlett, Ill., (www.wittenstein-us.com) lets engineers size and select gear reducers and motors for rack-and-pinion applications with just a few basic inputs.

User inputs include the mass to be moved, load angle, friction force, pinion size, material, and efficiency. The user defines the cycle as time/distance, distance/speed, or time/speed. Other inputs include the maximum acceleration or maximum acceleration period, dwell time, and external force/angle if there is one.

Cymex 5 calculates masses of combined components, mass moment of inertia, transmission ratios, rigidity, backlash, bearing life, mean and maximum speed and torque, and speed, acceleration, and torque profiles. It calculates the amount of backlash and compliance in the system components under loaded conditions. The software also lets users define motion characteristics, special features, and other operating requirements of the gear reducer and motor.

The software then generates motion profile characteristics. From there, the program recommends appropriate gear reducers and motors from its database of hundreds of servomotors and gear reducers. Once calculated, different drive variations and applications can be stored and recalled for comparison without recalculating the original drive system.

Set Up & Installation

There are many options for mounting rack-and-pinion sets Some racks need special mounting surfaces to ensure accuracy, while others deliver suitable performance even with basic installation. The design's inherent flexibility can be leveraged for better control. Unlike direct driving linear motors, rack-and pinion sets allow adjustments in pinion size, gear ratios, and damping to stabilize closed-loop control. There are pitfalls, however.

Putting the pinion and rack teeth too far apart causes backlash, which degrades precision. Compromised or misaligned mounting can also damage gearbox bearings, causing higher motor current draws, noise, and even failure. For best performance, a pinion should be properly distanced from the rack, mounted on a flat surface, and perpendicular to the gearbox to within about 25 μm for many applications.

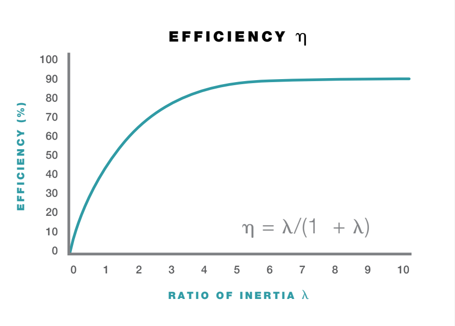
Advances in rack-and-pinion gearing and the decrease in servotechnology prices usually mean that servomotors are paired with rack-and-pinion systems. Stepper motors are a viable option, but servomotors are preferred for their precision.

SOME THOUGHTS ON INERTIA

Mechanical linear systems are typically quite efficient. But engineers who merely look at catalog efficiency ratings of components can get fooled if they assume total efficiency is the sum of the individual ratings. Users also need to consider the effects of inertia.

For instance, systems with a servomotor, coupling, and gearhead tend to have high moments of inertia and low mechanical stiffness. They require a low, robust inertia match—a ratio of the motor inertia to the load inertia of about 1:3—to perform well.

Actuators that eliminate couplings and mount the pinion directly on the motor shaft, in contrast, increase torsional and tilting fidelity and limit backlash. This reduces overall inertia, increases stiffness, and tolerates inertia ratios of 10:1. For the design engineer, this permits smaller motors for the same application and, in turn, smaller cables and drives, less energy consumption, and overall greater efficiency. One example of this is the TPM/RPM line of servoactuators from Wittenstein. Consider a simple system with a motor, gear pair, and load, and shafts directly connecting the three components. For dynamic tasks, torque requirements depend on the entire mass reacting in the drivetrain, so engineers must compare load inertia to motor inertia. The coupling factor λ, sometimes described as the ionertia match or mismatch, is a correlation of the external moments of inertia to the moment of inertia of the motor. Efficiency can be defined as $\eta = \lambda/(1 + \lambda)$.



The graph shows how obtainable power relates to drivetrain inertia. The coupling factor λ is a correlation of external power and motor inertias.

The drivetrain efficiency graphic shows that obtainable torque with respect to obtainable power is proportional to the mass moment of inertia in the drivetrain. It describes the total inertia in the system that must be accelerated in terms of power and efficiency.

Most people would think that a 1:1 inertia ratio would be an ideal match. But looking at the graph, only 50% of the total power is delivered to the load. It's really an inefficient system. With suitable controls, high stiffness, and low backlash, systems can tolerate higher inertia mismatches and use smaller motors for a given load-transferring more energy, a smaller, less-expensive motor requires less energy directly to the load. In addition to better efficiency, smaller, less-expensive motor requires less energy to produce the same output.