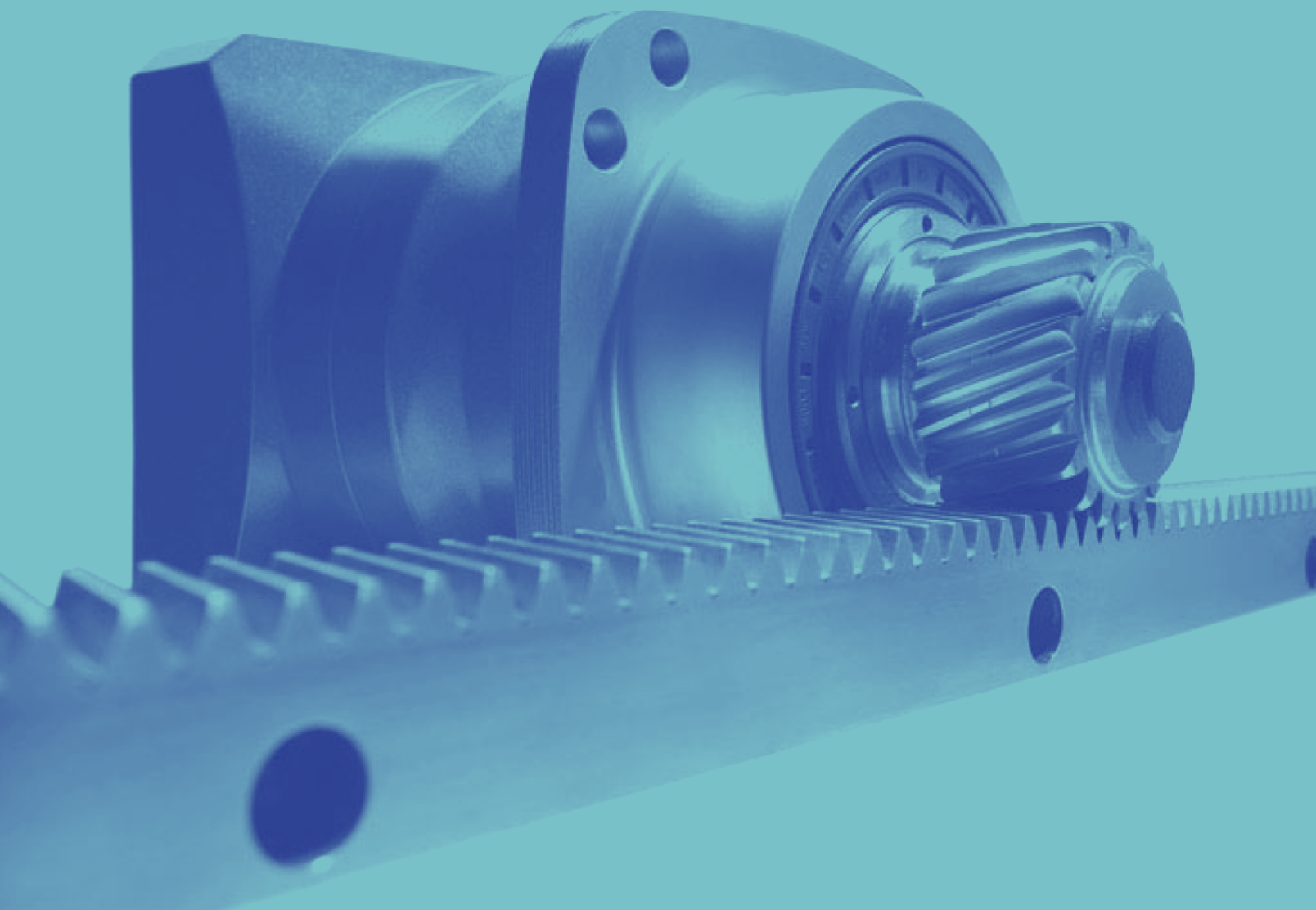


# Gearing Up for Efficiency

Power losses and inertia matching affect the efficiency of linear drives, slowing motion and increasing unnecessary wear. Wittenstein provides an in-depth examination.

By Miriam Metcalfe



THE OPERATING EFFICIENCY OF LINEAR DRIVES IS OF GROWING CONCERN TO MACHINE DESIGNERS. HERE'S A LOOK AT THREE COMMON LINEAR ACTUATORS—LINEAR INDUCTION MOTORS, ROLLED AND GROUND BALL SCREWS, AND RACK AND PINIONS—AND HOW THEY IMPACT A MACHINE'S OVERALL EFFICIENCY.

## BALL SCREWS

BALL SCREWS AND LEAD SCREWS HAVE BEEN AROUND FOR YEARS AND ARE USED 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 LEAD SCREWS AND HIGH-LEAD BALL SCREWS CAN BE NON-BACK DRIVABLE, MEANING THAT A VERTICAL-AXIS LOAD WILL LOCK IN PLACE AND NOT FALL IF POWER FAILS.

ON THE DOWNSIDE, A BALL SCREW CAN BE TREATED AS A LARGE SPRING 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 THE MAXIMUM 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 that hurts performance. Maximum axis length is typically around six meters. It also means linear stiffness is not constant but depends on the 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, it can make the screws noisy. Shortstroke applications prevent complete recirculation of the balls. In such cases, dynamic loads must be derated.

## LINEAR MOTORS

Linear motors gained wide use in the 1980s with rapid technical advance and the introduction of many innovative products, though the pace of development has tapered off of late. A prime benefit is the moving carriage of a linear motor typically has low mass, permitting high acceleration

rates and peak speeds. It also saves time when motion frequently changes direction. Brushless linear motors run quietly and the drive systems typically have long lives.

On the downside, despite improvements linear motors are still rather inefficient, and energy consumption is up to five times that of similarly rated rack-and-pinion actuators. Higher energy demands may mean higher up-front infrastructure investments, as 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 to cost and complexity and further hurts overall system efficiency. Heat generation can be extreme in low-speed/high-force operations, such as drilling.

Because of their direct-drive nature, 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, oscillations or resonances can result if external loads induce position deviations. Without the reduction in inertia and damping inherent in a mechanical system, controls issues may surface at the work piece.

## HORIZONTAL DRIVE

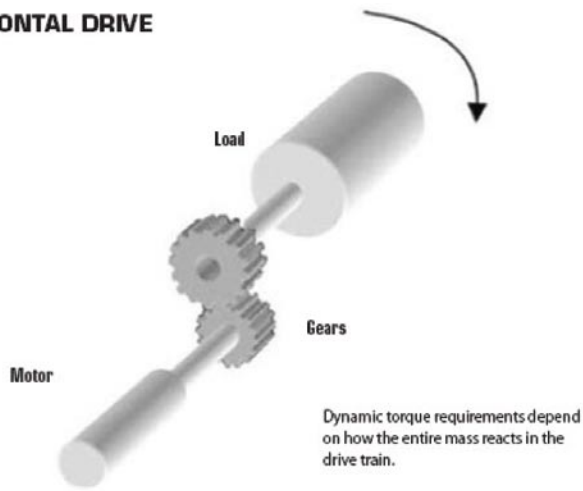


Fig. 1: Horizontal drive.

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

Engineers should weigh a linear motor's potentially higher

investment and energy costs 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.

## RACK AND PINION

Rack and pinion drives have been around for centuries, but recent developments in electronic boosted overall performance and energy efficiency. Advantages include long-term, backlash-free operation and unlimited travel length. In fact, a significant benefit over other designs is lower costs over long travel lengths. Helical gearing gives smooth engagement of teeth and quiet operation. Smooth running also helps ensure good part quality and surface finish, for instance, when machining tight-tolerance parts. For high-precision systems, single-pitch error between helical teeth can be around 3  $\mu\text{m}$ , and cumulative pitch error only 12  $\mu\text{m}/500\text{ mm}$ .

Rather than connecting the drive directly to the workpiece, the 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 optimize performance and efficiency. On the downside, the rack must be kept clean

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and lubricated, and the lube can splash at high speeds.

Rack and pinion actuators often have acceleration rates and peak speeds nearly as good as those of linear motors. In many cases, the machine frame and structure—not the actuator—limit peak speeds from rack-and-pinion and linear-motor systems. Ball screws tend to have somewhat lower peak speeds and accelerations.

## THE IMPACT OF INERTIA

In general, linear motors have overall efficiency as high as 85 percent, though some are considerably lower. Ball screws, depending whether or not preloaded, can have efficiencies up to 90 percent. Rack and pinion systems can push efficiency to 97 percent.

Mechanical linear-motion systems are, therefore, typically quite efficient. But designers 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 on the system.

For instance, a system with a servomotor, coupling, and gearhead tends to have a high moment of inertia and low mechanical stiffness. Such systems 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 the coupling and mount the pinion directly into the motor shaft, in contrast, increase torsional and tilting rigidity and limit backlash. This reduces system inertia, increases stiffness, and tolerates inertia ratios of 10:1. For the system designer, that permits smaller motors for the same application and, in turn, smaller cables and drives, less energy consumption, and overall greater efficiency. Here's a look at the underlying math.

Consider the simple “horizontal drive” system shown in fig. 1. For dynamic

tasks, torque requirements depend on the entire mass reacting in the drive train, so designers must compare load inertia to motor inertia. With  $J_M$  = motor inertia,  $J_L$  = load inertia, and  $i$  = gear reduction ratio, the necessary moment for a given acceleration depends directly on the sum of the moments of inertia,

$$J_T = J_L + i^2 J_M.$$

The coupling factor  $\lambda$ , sometimes described as the inertia match or mismatch, is a correlation of the external moments of inertia to the moment of inertia of the motor.

$$\lambda = J_L / (i^2 J_M);$$

$$J_M = J_L / (i^2 \lambda);$$

$$J_T = J_L + J_L / \lambda = J_L (1 + 1 / \lambda).$$

With torque  $M = J\alpha$  and  $\alpha$  = angular acceleration, total power in the system  $P_T$  and power delivered to the load  $P_L$  relate as:

$$P_T = P_L (1 + 1 / \lambda);$$

or efficiency is

$$\eta = P_L / P_T = \lambda / (1 + \lambda).$$

The “drivetrain efficiency” graphic in fig. 2 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.

## ELECTRONIC PRELOADING

Most people would think that a 1:1 inertia ratio would be an ideal match. But looking at the graph, only 50 percent of the total power is delivered to the load. It's really an inefficient system. With robust controls, high stiffness, and low backlash, systems can tolerate higher inertia mismatch and use

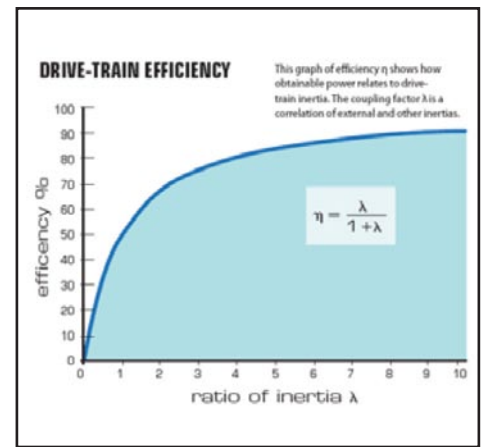


Fig. 2: Drivetrain efficiency.

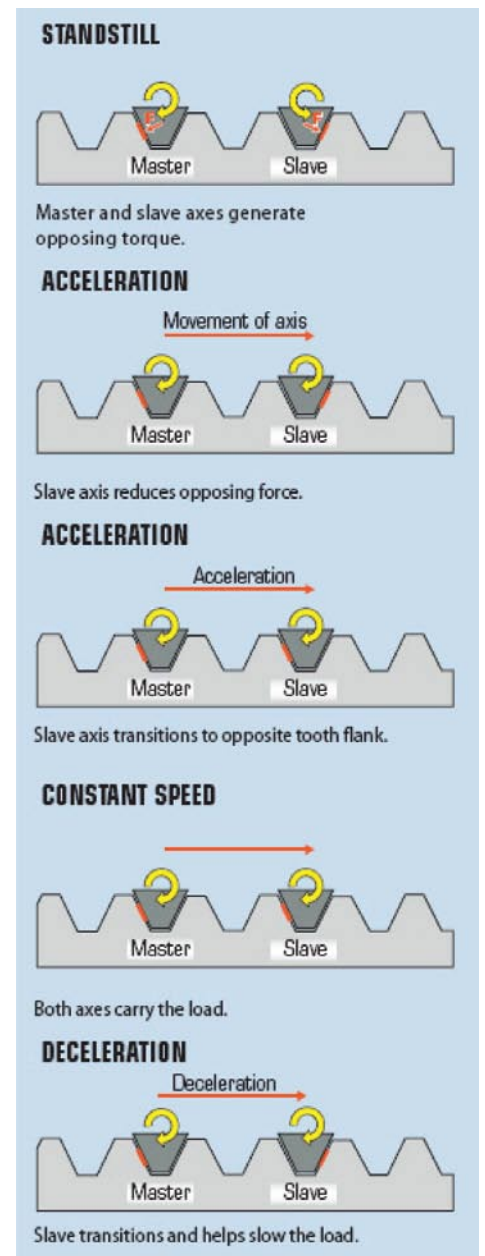


Fig. 3: The four stages of motion.

