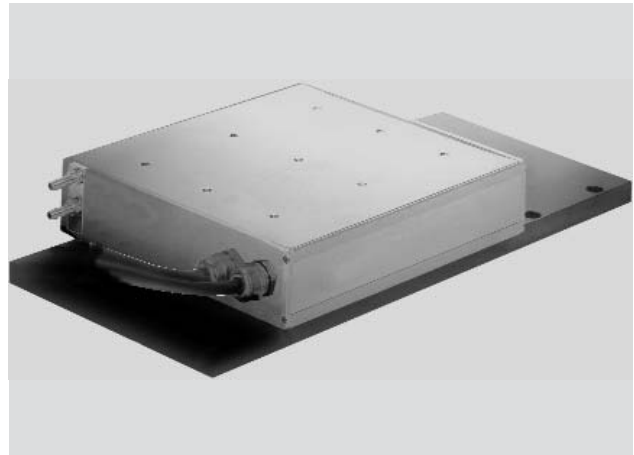
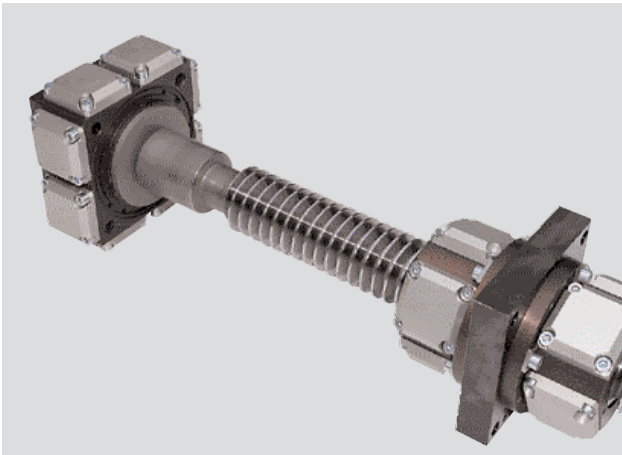


Hydrostatic lead screw

in comparison to linear motor and ballscrew



The weakness of ballscrews have resulted in the development of linear motors and high load capacity and wear-free hydrostatic lead screws by the company HYPROSTATIK Schönfeld GmbH. The hydrostatic lead screw is presented and compared with linear motor and ball screw in the following.

While there was already disillusionment if not disappointment after the initial euphoria for some users of linear motors, all of the several hundred hydrostatic lead screws installed, some also in three-shift operation since 1996, have been operating with the highest precision and reliability.

1. The hydrostatic lead screw

Like a ball screw, the hydrostatic lead screw converts the rotary movement of a servomotor into a linear movement. The nut of the lead screw floats on a hydrostatic oil film and is thus absolutely wear-free. Using the oil flows controlled by the PM regulator, the oil film thickness is maintained practically constant irrespective of the speed and load. The play-free hydrostatic nut is extremely stiff and, in spite of this, has very low friction. At low speeds, for example during positioning, the friction is practically zero. The position accuracy, the smallest traverse path and the slowest speed are thus only dependent on the measuring system and the controller. Compared to the dynamic load, the hydrostatic ball screw acts as a shock-absorber with excellent damping. It operates absolutely silently and the well-known vibrations from ballscrews do not occur.

The hydrostatic lead screw is available with rotating spindle or rotating nut in the sizes 40 to 160 mm, for axial forces 10 to 300 kN, speed up to 120 m/min, up to a length of 4 metres in different slopes and with spindle ends manufactured according to customer information. Hydrostatic lead screws are complemented by hydrostatic fixed and floating bearings and guides. ■

2. Physical basic principles

Electrical energy can be converted to mechanical energy very effectively with relatively low forces and high speeds. For this reason, fast running motors with lead screws for producing slow slide speeds and high feed forces are usually used for feeder drives. Thus, the power of the motor is transmitted to the slide via a very large lever. With a corresponding quality of the transfer element, the slide can be delicately adjusted with small forces.

This principle is abandoned by the linear motor. For the direct generation of large forces, extremely strong magnetic fields must be produced, which can only be achieved by electric currents and/or by coils with high inductivity. As coils with current flowing through them represent an electrical mass, a large electrical mass must also be alternately accelerated for dynamic load changes even if the slide only has to be maintained in position. Also, if high voltages are used for changing the magnetic flux, the change in the motor force is time limited.

This problem only exists to a small degree with lead screw and servomotor as the electric currents to be controlled are very much smaller than for the linear motor. ■

3. The stiffness for static and dynamic load

The stiffness of the linear motor resulted exclusively from the position control of the drive in combination with the necessary linear scale. Without positioning control circuit, the stiffness of the linear motor is zero!

In comparison with static load, the stiffness of the linear motor is infinitely high. However, this also applies to a drive with hydrostatic lead screw controlled using a linear scale.

The “dynamic” stiffness of the linear motor is low due to time delays by relocation measurements, reaction time of the controller and build-up of the magnetic field. According to information from one linear motor manufacturer, the dynamic stiffness is between 39 N/μm (for a slide weight of 100 kg) and 120 N/μm (slide weight 600 kg) without mention of the frequencies. There is a danger of resonance oscillations for oscillating slide loading due to the missing damping in the direction of movement.

In contrast, the stiffness of a drive with the hydrostatic lead screw with a nominal diameter of only 50 mm with a spindle length of 400 mm is 350 to 400 N/μm and significantly higher if the spindle is clamped on both sides.

Together with the high damping and the higher total mass of the feeder axis of the hydrostatic lead screw resulting from the inertia torque of the spindle, several times smaller oscillation paths or dynamic position deviations are achieved with this drive than with the linear motor. Path oscillations of the hydrostatic lead screw also die away very quickly due to the excellent damping. ■

4. The maximum acceleration

There are no component conditional acceleration limits for the hydrostatic lead screw and linear motor. The maximum acceleration is limited by inertial forces and feed pressures. The service life of the hydrostatic lead screw is not reduced by the acceleration.

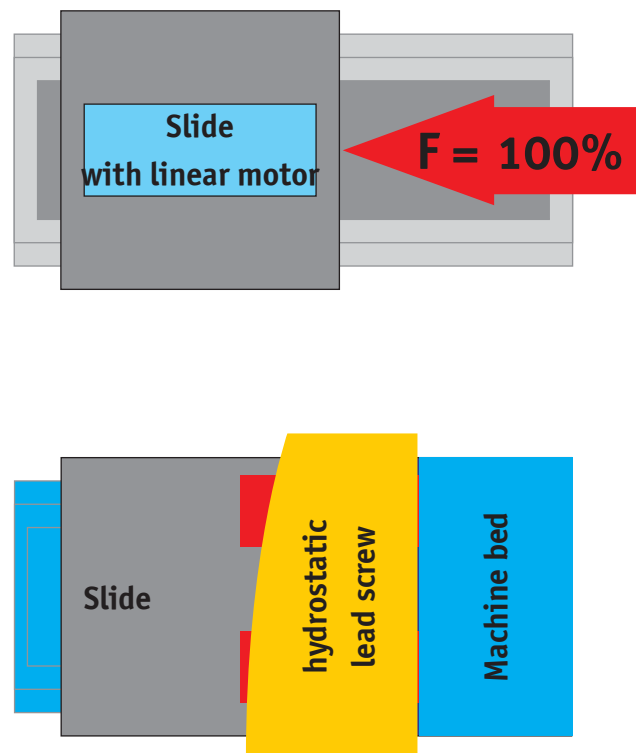
The servomotor must also accelerate its own inertia torque and that of the lead screw. Nevertheless, modern servomotors can accelerate 500 or 1000 kg heavy slides with traverse lengths of 500 or 1000 mm at 16 to 34 m/s².

Significantly higher acceleration values are also possible for optimised short-stroke slides. ■

5. The feed pressure

The maximum continuous feed pressure of approx. 8 kN of the largest linear motor is not sufficient for a large part of the applications in machine tool manufacturing. With hydrostatic lead screws of the size 50 mm, up to 20 kN can be applied and up to 300 kN with the size 125!

As regards the possible feed pressures, the hydrostatic lead screw is far superior to the linear motor! High loads even with very slow, extremely fast or oscillating movement do not adversely affect the function and service life of the hydrostatic lead screw in any way. ■



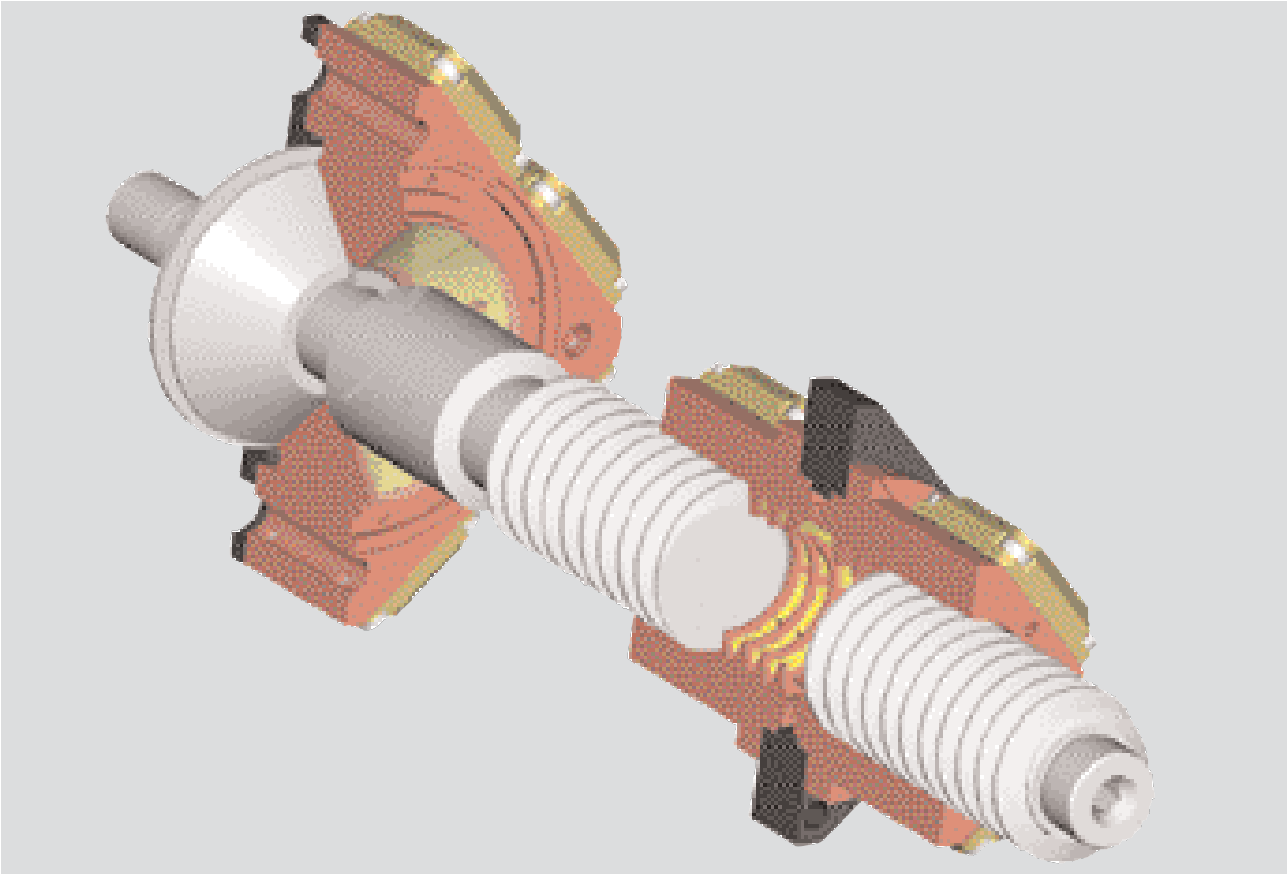
6. The maximum slide speed

The maximum speed with the hydrostatic lead screw is

- approx. 40 m/min with 10 mm slope,
- up to 80 m/min with 20 mm slope,
- up to 120 m/min with 30 mm slope.

With a rotating spindle, the maximum speed is limited by the critical speed, however, hardly at all when using a rotating nut.

The maximum slide speed of the linear motor at rated load is stated as 60 to 200 m/min accelerations. However, it is limited when using the linear motor by the safe management of the kinetic energy of the slide also in the case of a power cut, the risk of destruction during a crash and by the possible risk of accident. ■



7. Usefulness of high accelerations and speeds

For most machine tools, high slide speeds and accelerations are not needed during the machining process, but only for reduction of the auxiliary process times.

Reduced auxiliary process times using higher acceleration than 10 m/s^2 for average processing times are only somewhat expedient. Higher accelerations should then only be provided if they are necessary for the machining process or for extremely short processing times.

Increasing the speed of the slide from 20 to 40 m/min is expedient. A routine fast track of approx. 400 mm should be traversed for a further increase from 40 to 60 m/min. An increase to 80 m/min only appears to be expedient for routine fast tracks greater than approx. 800 mm.

Acceleration of 20 m/s^2 and speed of 120 m/min can be achieved with the hydrostatic lead screw. For most machine tools, it makes sense to achieve better machining results, longer service life, lower range of temperature, reduced maintenance and electricity costs with slightly lower speeds and accelerations. ■

8. Energy requirement, heat input, cooling

For most machinings, a low slide speed of approx. 0.1 - 0.4 m/min and a high feed pressure are required during the primary processing times, which require the most time.

The cooling capacity of our comparison linear motor for these low feeder speeds with 6,600 N nominal force is **5.4 kW** according to the manufacturer information. A cooling unit capacity of approx. **2.1 kW** is needed for recooling this capacity. Thus, altogether approx. **7.5 kW is needed while a feed pressure of only 6,600 N is achieved!**

A typical hydrostatic lead screw for higher speeds requires an oil flow of approx. 2.0 l/min at e.g. 50 bar pump pressure. A capacity of approx. **0.45 kW** for driving the pressure pump and the air-oil heat exchanger and a capacity of **0.14 kW** for the servomotor at 400 mm/min feeder speed, 10,000 N feed pressure and 50 % efficiency are needed. Thus there is a power requirement of approx. **0.6 kW**.

A much higher feed pressure, but leakage power reduced by 6.9 kW as compared with the linear motor!

For average usage with only one single axis and an electricity price of 0.08 Euro / kW and 2000 operating hours per year, there would be estimated additional costs of 750 Euros per year and 2.250.080 Euros per year for three-shift operation. **If these costs are capitalised with a rate of**

12 % for interest and depreciation, these costs equate to investments of **6,250 Euros** or **18,750 Euros per axis**. Even with a few machines with linear motors, additional costs for the power supply, e.g. for a separate transformer station, are probable. Thus, the energy costs must absolutely be taken into account for a comparative examination.

The linear motor must usually be arranged under the slide. The enormous heat output of the motor must be kept away from the slide by water cooling and insulation, otherwise the heat input results in unacceptable inaccuracies.

In contrast, the servomotor of the hydrostatic lead screw is usually arranged outside the axis so that the heat transfer to the axis is minimal. Thus, an external fan is usually sufficient for the motor cooling; water cooling is only required in special cases. The energy input to the oil by pump and friction of the hydrostatic nut is typically, even for fast slide movements, only approx. 60 to 120 Watt and is predominantly discharged with the oil. The oil continuously tempers and cleans the threaded spindle. An air-oil heat exchanger is only needed for high slide speeds and/or high demands on the thermal stability of the machine. ■

9. Comparison with ball screw

No very high accelerations and also no extreme speeds and oscillating movements are possible with ball screws for an acceptable service life, particularly on account of the ball deflection.

The ball screw has only minimal damping and wears, whereby position dependent differences for friction, stiffness and changeover jump are produced.

In the case of a crash, ball impressions can be produced on the tracks, which force premature replacement of the ball screw spindle.

A significant torque jump occurs when changing the direction of movement due to the pre-tensioning of the nut. The friction torque of ball screws varies due to the ball run-in and run-out. Due to this torque jump and its different size, precise position control, the defined traverse of small paths and moving at very low speeds are only conditionally possible with the ball screw.

The hydrostatic lead screw does not show all these disadvantages! Acceleration with hydrostatics is not limited and the hydrostatic nut can be optimally designed for every application by selection of oil viscosity, pressure and flow rate. The hydrostatic lead screw is wear-free, slow movements (also with high load and oscillating movements) are no problem for the highest frequencies and oscillation speeds. The damping of path vibrations by the hydrostatic nut is magnificent. ■

The crash safety is far higher than that of the ball screw, however, the hydrostatic lead screw can be damaged by a crash.

As measurements by the “Werkzeugmaschinen und Betriebstechnik (machine tools and operating technology)” have shown, the stiffness of the hydrostatic lead screw is significantly higher than that of comparable ball screws and does not change by wearing. Despite this, the hydrostatic lead screw friction is very small and also proportional to the rotation speed, whereby no torque jump of any kind occurs when changing direction.

If hydrostatic bearings are also used at the ends of the lead screw and the slide is guided hydrostatically, the servomotor thus has no friction of any kind to overcome even at low speeds and when changing the direction of movement. The hydrostatic drive and guidance system thus also enables the gradual and oscillating traverse of the slide by fractions of μm and extremely slow traverse, which are of course completely independent of the load. ■

10. Vertical axes, power cut

Braking the linear motor, even with a brake van, is problematic in the case of a power cut or motor failure.

In contrast, with the integrated brake in the servomotor, **much higher braking forces** can be applied via the hydrostatic lead screw.

In addition, the lead screw with normal slope (nominal size 50, 10 mm slope) has the advantage over the ball screw of self-locking when the hydrostatic oil supply is switched off. For dynamic vertical axes without weight compensation, the linear motor needs much higher amounts of energy to stop the mass than the drive with lead screw (see point 8). ■

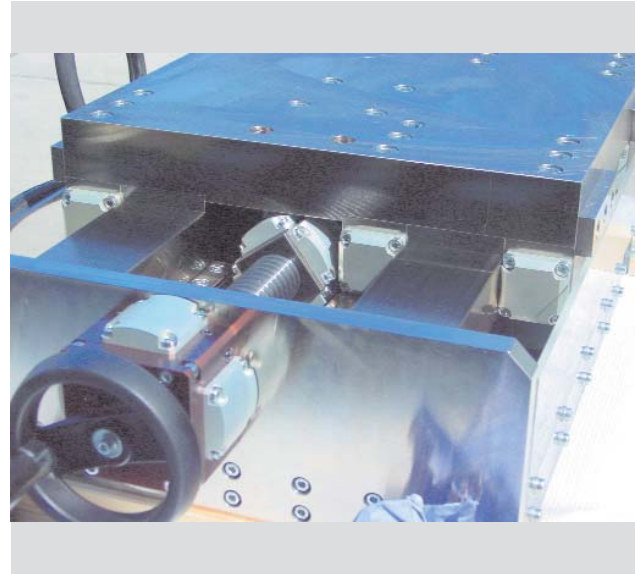
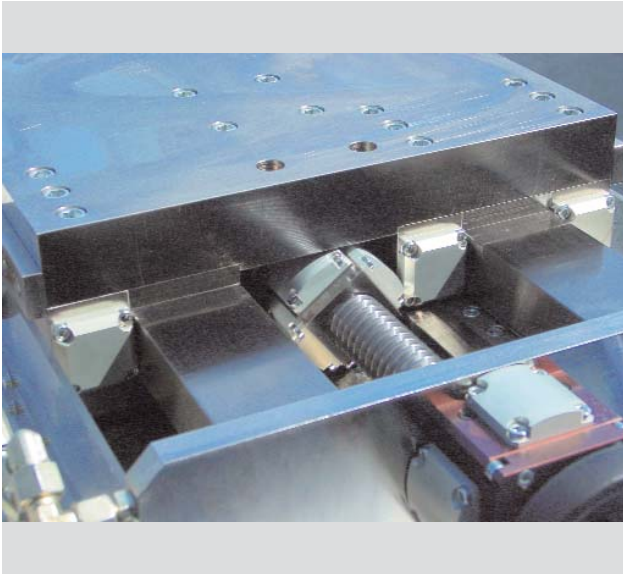
11. Guides

The guides of linear motor axes are strongly **charged with high magnetic forces**, the forces also have an effect even when the machine is switched off. This load varies and is a multiple of the maximum motor power, in comparison approx. 40 kN. In conjunction with high speed and acceleration, the service life of roller guides is reduced.

Thus, multiple hydrostatic guides instead of roller guides are used for linear motor slides.

Like the lead screw, the hydrostatic guides operate **absolutely wear-free** and have a 20 to 1000 times lower friction force proportional to speed and independent of load.

There is **no force jump** of any kind by the guide when the direction of movement changes. Thus, for a corresponding



quality of the drives and control systems, gyrations with path deviations in the range of $0.1 \mu\text{m}$ are possible with “completely hydrostatic” cross slides, whereby completely new machine concepts are possible, e.g. jig boring machines, coordinate grinding machines. ■

12. Special features of linear motors and hydrostatic lead screws

Magnetic chips are attracted by the strong magnetic fields of the linear motor components and can cause faults later. Therefore, better covers are needed for linear motors.

The installation, maintenance and replacement of the linear motor integrated in the machine are significantly more complex than for the externally attached servomotor, which can be replaced **without dismantling the axis**.

Due to the strong magnetic fields of the linear motor, **additional measures for the protection** of certain groups of people (for example, those with heart pacemakers, metal implants or pregnant women) and objects, which can be affected by magnetic fields (data media, watches, credit cards) are required.

The high permanent magnetic forces also cause problems during installation: The motor suppliers recommend always keeping some non-magnetic wedges available during installation so that the motor components can be separated from each other in the case of an accident!

In addition, the machine manufacturer is bound to the linear motor manufacturer, which in many cases results also in liaison with only one control system manufacturer.

The oil necessary for operating the hydrostatic lead screw must be fed back into the power unit. Either it is fed back into a pipeline by a nut fitted with a wiper ring or it flows back into the tank together with the hydrostatic guide oil. The

same oil at the same pressure from the same power unit can be used for the guide, the lead screw and the lead screw bearing and can still be used for other hydraulic or lubrication tasks.

Machines must be completely redeveloped for using with linear motors.

Hydrostatic lead screws with low complexity can be used instead of ball screws. If the somewhat larger nut of the hydrostatic lead screw is taken into account during the new design, the customer can optionally choose a ball screw or the hydrostatic lead screw. ■

13. Price comparison

A correct comparison of prices is dependent on the details. As compared with the ball screw, additional costs for the hydrostatic lead screw accrue due to the lead screw and negligible ones from the power unit and cover.

In most cases, the hydrostatic lead screw with servomotor is significantly more economic than the linear motor, which causes much higher costs mainly due to the costs for motor components, cooling plates, peripheral equipment, linear scale, complex control system, large cooling power units and the modified or new design of the machine.

Most of the lead screws installed to date **have significantly reduced the costs for the machine users as the hydrostatic lead screw in 3-shift operation even after more than 5 years is as good as new**, whereas a ball screw in this period would possibly have been replaced several times. For long traverse paths, the linear motor is more expensive due to the permanent magnets. ■

14. Applications

Nine years after the first delivery, there are today approx. 250 lead screws installed per year as the standard in many important, European cam, crankshaft, universal, ultra precision and cog wheel grinding machines.

Noncircular machinings with over 60 Hz and 3,000 rpm at the work piece have been realised. Lead screws with 340 kN axial force and 3.5 m long machine internal gear tooth forming in broaching machines for automatic gearboxes.

There is a milling machine in the "Machine Tool Research Center" in Florida, which is fitted with hydrostatic lead screw and guides.

The Fraunhofer IPT in Aachen uses hydrostatic lead screws, fixed and floating bearings and hydrostatic guides in an ultra precision machine. ■

15. Summary

Ball screws are limited in positioning accuracy, stiffness, acceleration, speed, load capacity and service life.

In the wide range of applications for machining and rapid traverse speeds up to 80 m/min, the hydrostatic lead screw is technically and economically superior to the linear motor.

The alternative to the ball screw and linear motor is the hydrostatic lead screw. It reaches speeds up to 120 m/min, accelerates like a linear motor, however, has a 10 times less energy consumption for the typical infeed for machine tools.

With the same acceleration, the hydrostatic lead screw provides multiple feed pressures in comparison. It has excellent damping, a linear scale is not absolutely necessary.

The dynamic stiffness of the linear motor of 30 to 120 N/ μ m is very low. The stiffness of a hydrostatic lead screw nut nominal size 50 mm and of the fixed bearing is 1,200 - 2,000 N/mm, the dynamic stiffness is even higher. The required oil flow rate of 1-2 l/min for the hydrostatic nut can be fed back with little complexity.

With hydrostatic guides, both systems can position very precisely, however, the linear motor has problems with maintaining the position during impacts and dynamic loads.

The enormous leakage power of linear motors results in very high temperatures under the slide, it must be cooled with large and expensive cooling equipment.

Metal chips are held by the permanent magnets and can damage primary and secondary parts. The same chips on the hardened non-magnetic lead screw in contrast are pushed away.

The hydrostatic nut cleans and tempers the screw continuously.

The linear motor permanent magnet forces on the roller guides result in premature wear if no hydrostatic guides are used.

There are significant dangers from the linear motor components during installation.

A servomotor of an hydrostatic lead screw is easy and significantly less complex to replace than a defective linear motor. Motors and control systems from different manufacturers can be used on the same machine with lead screws.

Apart from some HSC machines where high speeds and accelerations are required, acceleration values of more than 10 m/s² only make minimal time savings possible, extreme values of the speed more than approx. 20 to 30 m/min only permit small time savings (in many cases, this saved time does not justify the extra cost for suitable machines, particularly those for higher accelerations).

The euphoria with which the electric linear motors were greeted does not, however, seem understandable in view of the facts described above. ■

We therefore recommend to also consider the classic feeder drive with lead screw and hydrostatic nut and also hydrostatic axial bearings for the threaded spindle as alternatives to the linear motor!