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DRIVING SYSTEMS – FROM GEARBOXES TO DIRECT DRIVE

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Abstract: *The simple things are the most difficult - it has been found by a lot of specialists. For simplifying more and more the driving mechanism, the mechanical engineers are very much helped by electric motor builders. The direct drive concept has been materialized in rotating motors (main driving and feed driving systems) and linear motors. In this paper the design, advantages and shortcomings of these motors, problems to be solved when using them and application fields are shown.*

Key words: *machine tools, driving system, torque motor, linear motor, direct drive application.*

1. INTRODUCTION

In his whole existence the human being needed movement for getting all necessary means for material and spiritual life, for exploring the space. The means and the methods for movement accomplishing are extremely different, beginning with his force up to those assuring the travel towards and in the space.

The paper has in view a much narrower area: machine tools and especially direct driving systems. For underlining the importance of the direct driving systems their applications in various areas will be presented too. Traditionally, servo drives use high speed rotary motors in combination with mechanical transmissions. These motors are designed to run efficiently at high speed where cogging, speed ripple, and torque ripple are not serious issues. Mechanical transmissions are used to transform the high speed motion of the motor into the low speed, high torque operation required by the application. The gearboxes are expensive, noisy, produce torque ripple and require additional maintenance.

Replacing these systems with direct drives (torque or linear motors) considerably increases performances of the systems, and also maintenance and operating costs are radically reduced when implementing direct drive.

2. DIRECT DRIVE SYSTEMS

Direct drives eliminate the need off mechanical transmission elements and enable a direct coupling of the payload to the drive. This enables a drive with high dynamic response without hysteresis.

These direct drive systems can be used in: rotary or indexing tables, pick and place robots, grinding machines, wind/hydro generators, elevators, telescope or radar stations and many other applications.

2.1. Torque motors

The most unique feature of a torque motor concerns the physical dimensions. They have a relatively large diameter to length ratio, and they also have a rather short axial length. Additionally, torque motor can simultaneously have both a very large outer diameter and inner diameter, resulting in a motor that is a thin ring.

One important outcome of this characteristic is that the mass is quite low as a function of the diameter. Also, the large diameter allows very high torque to be developed.

2.1.1. Motor construction

A torque motor is a rotary brushless servomotor optimized for low speed operation. It has a high number of poles, output speed less than 1000 rpm. There is no need for mechanical transmission element such as a gearbox.

There are two different kinds of torque motors:

- Frameless motors made up of two independent elements (rotor + stator) intended to be integrated into the mechanics (Fig. 1). This means that the motor does not include a housing, bearings, or feedback device. In this sense the motor is a “kit” motor, meant to be an integral part of the machine structure. To assist in integrating torque motors, they can be provided with a reusable assembly aid called a “bridge” [2]. The bridge is set at the factory to ensure the proper alignment of the rotor and stator for assembly.

The bridge also keeps the magnetic field contained within the motor, thereby eliminating the need for a special non-ferrous area for assembly, and protecting the rotor from damage from metal scraps or loose screws – Fig. 2.

Fig. 1. Frameless torque motor [1].

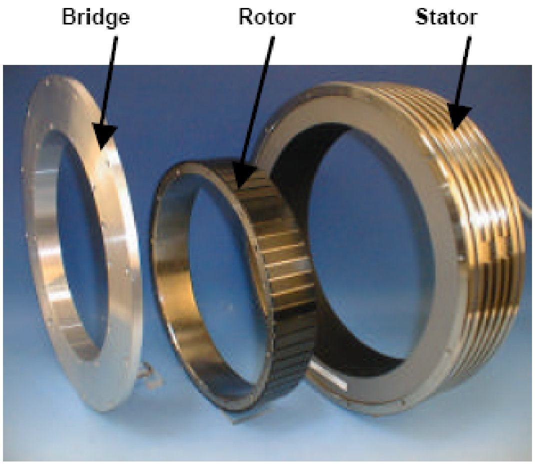

Fig. 2. Frameless direct drive motors [2].

Fig. 3. Complete torque motor [1].

- Complete motor with frame, cooling system, terminal box and feedback sensor – Fig. 3.

Complete systems can be used if there is a desire to take advantage of the benefits of direct drive systems without additional design overhead. This is especially true in the case of special machine construction and setting up testing systems.

Direct drive – meaning no or few power transmission elements between motor and driven load – brings advantages of high dynamic motion with essentially no backlash and excellent static/dynamic load stiffness that allows precise motion control.

Torque motors are available in a wide range of sizes, with diameters from smaller than 100 mm to greater than 2m (though 1.2 m is typically the largest for machine tool applications). At the top-end, more than 20,000 Nm peak torque output is not unusual.

Torque is proportional to rotor diameter squared and directly proportional to rotor length. Large number of permanent magnets on the rotor enables the motor to be constructed as a thin ring. It also enables torque motors to achieve very smooth velocity regulation, with low ripple.

Torque motors have the same control characteristic as other brushless PM motors. However, by eliminating mechanical elements in the drive line, backlash (lost motion) and mechanical ″weaknesses″ also are eliminated. The result is a dramatic increase of the drive overall stiffness.

High torque output produces heat in the motor windings that must be removed to avoid motor damage. Cooling also minimizes heat-related expansion, primarily of the motor stator.

Other reasons for OEMs to apply these torque motors include less maintenance and spare-part inventory with fewer parts used in the construction, energy savings from a more efficient driving system, and space savings with smaller foot print machines versus a motor-gearbox combination.

Besides new processing technologies or even higher-performance, decentralized control systems, direct drives offer the highest potential for improving the performance of modern machine tools and other manufacturing machines. By connecting the drive as close as possible to the load, a lot of mechanical transfer elements are eliminated. This provides multiple benefits to the user:

- Rising productivity because of significantly increased drive dynamics.
- Increased product quality with second-to-none control quality and positioning accuracy.
- Lower life cycle costs through the elimination of parts subject to wear and tear.
- Simplified project planning and machine construction

The demand for product quality and machine output is constantly rising. The direct integration of drive technology into the process – without any compliance or elasticity that reduces quality is critical for control systems and allows for significant improvements in this area. In some cases, electro-mechanical direct drives replace hydraulic solutions. The result is an environmentally-friendly solution that is also easier to install. Direct and jerk controlled drive technology increases the availability of the machine.

In the case of direct drives, stiffness is achieved by feedback of the motor position signal to the position and speed control circuit. The lack of a mechanical reduction ratio causes the effects of external forces to be significantly greater than for conventional linear drives with rotary motors. Because of this, the quality of the position signal (resolution and precision) and the output capacity of the servo controller (scanning time, control algorithms used) are decisive factors in determining the level of position stiffness that can be achieved with direct drives.

2.1.2. Applications

Although not a high-volume product, torque motors range over wide applications. Fields where they gave good results are, for instance: machine tools, machining centers, metal forming, rotary transfer systems, printing/converting machines, plastics extrusion/injection molding machines, and in the printing industry – Figs. 4, 5, 6, 7, and 8.

Non industrial applications include wind power generation and wave power harvesting. Also its can be used in ocean wave power conversion and in new-generation elevators, replacing hydraulic solutions with lower maintenance cost and simpler installation benefits.

In short, torque motors are at home anywhere traditional gear trains, chains, or timing belts have been used in the past.

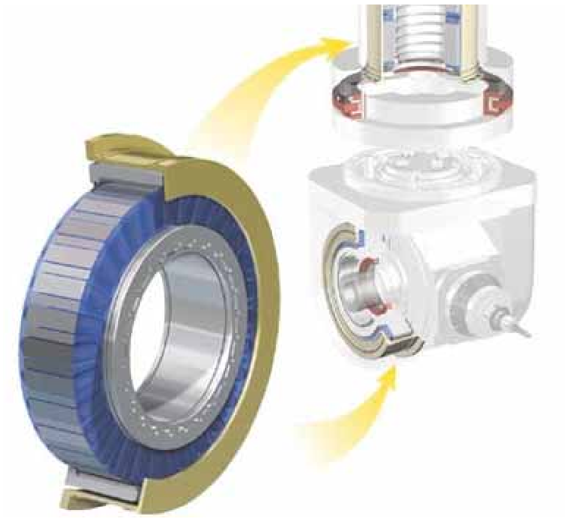

Fig. 4. Two torque motors integrated into a milling head [3].

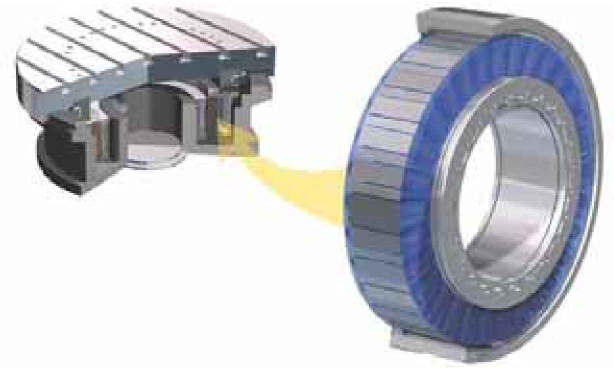

Fig. 5. Torque motor integrated in a round table [3].

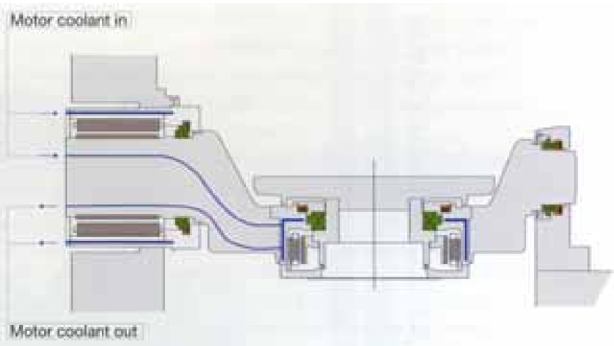

Fig. 6. Torque motors in machine tools [7].

- Manufacturers of direct-drive brushless torque motors firmly believe that users can gain major productivity and quality benefits if their machine design is optimized to apply these motors.

It describes a motors ability to produce torque as a function of heat. This goes up with the square of the torque. This power produced is solely from Joule loss in the copper winding and does not describe the heat produced by iron loss. In most applications, Joule loss is the predominant loss, except when the motor is moving at a very a high speed.

A motor with a higher value of K_m is a more efficient producer of torque.

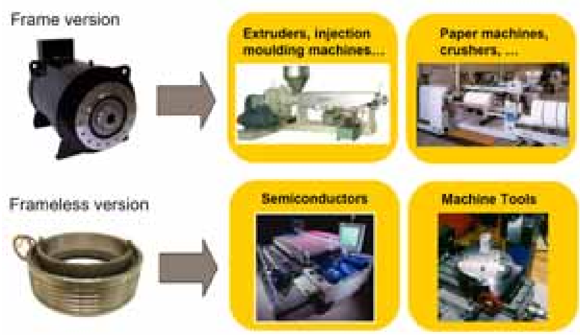

Fig. 7. Different applications.

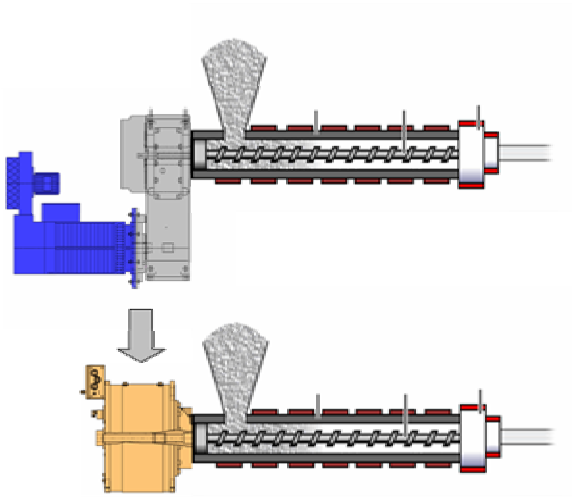

Fig. 8. Replacement of a geared based system for extruders with torque motor [1].

The most important parameter of a direct drive motor is the motor constant K_m:

$$K_m = \frac{\text{Torque}}{\sqrt{\text{Copperlosses}}} \left[\frac{\text{Nm}}{\sqrt{\text{W}}}\right]. \quad (1)$$

2.1.3. Thermal considerations

One must look at the thermal dynamics of the motor system because a motor usually has a maximum operating temperature. The total surface area of the motor must be able to dissipate the total power loss in the motor, while keeping the temperature below the manufacturer's maximum rated temperature.

It is much important to remove the heat in direct drive systems than in a conventional one, where the motor is typically mounted in a location where the heat removal is easier. An effective solution is to use liquid cooling to remove the heat. This method increases the continuous rating of the motor.

2.1.4. Feedback requirements

High precision, high-resolution feedback is essential for optimal performance of a direct drive. Because the load is directly coupled to the drive higher accuracy is possible, but the positioning resolution is also in direct relation to the resolution of the feedback system. One needs an optical encoder with a high line count (typically 9,000 lines per revolution and above), combined with a high-resolution interpolation factor.

Such feedback devices are available from several manufacturers. System resolution below 1 arc-sec is generally required [2].

2.1.5. Project development

Complete systems come as plug and play units. In addition to the actual motor, additional elements such as the feedback device, bearing system and cooling are already integrated and fully compatible with each other in these systems.

In contrast to a complete system, the frameless motor is a fundamental element of the overall design. The feedback device, bearing system and methods of cooling are selected after taking into consideration the specific conditions.

The machine construction should meet the following requirements:

- small moving mass;
- good foundations;
- rigid machine design with high natural frequency;
- good damping in the overall structure;
- careful integration of the feedback device (rigid attachment);
- contamination-resistant housing for motor and feedback device.

Questions on mechanics:

- cable guiding, cable carrier chain;
- oscillation behavior, natural frequency;
- arrangement of the motor;
- heat dissipation and cooling;
- horizontal or vertical application;
- mechanical limits (speed and acceleration);
- movable mass;
- friction and frictional forces.

Among companies who use direct drive motors in their machinery are: Breton, JOBS, Zimmermann, Tornos, Ona, Agie Charmilles, Willemin, Dihi, Bumotec, Rgi, Forest Line, Gnutti, Acutronic, Acuitas, Arc International, Atn, Automatex, Avitronics, Comau (Group FIAT), Cuir CCM, DCM, Demag, DMG, Eoltec, Escofier, Finnwind, Gallileo Avionica, Hoefler Maschinenbau, Huron Graffenstaden, Michelin, Mori Seiki, Dixi Macchines, Morphic, Negri Bossi, Otis, Peiseler, PSA, N.Schlumberger Group, SMP, Sony Dadc, Starlinger, Staubli, Steag Hamatech , Tetrapak.

We can enumerate different companies who produce torque motors: Parvex, Etel, Siemens, Kollmorgen, Indramat, Oswald, Powertec, NSK, Parker, Alxion, INA Shaeffer, AMK, Zimmermann, etc.

Fig. 9. Torque motor – ICPE.

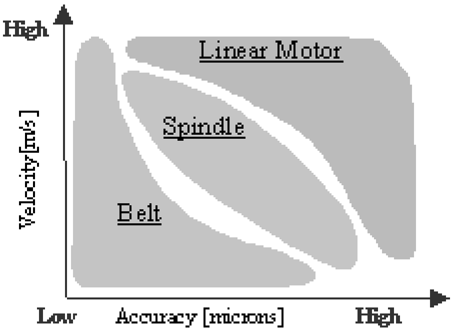

Fig. 10. Velocity versus accuracy.

In Romania, ICPE [4] has developed two direct drive motors for radars, one type with 1,100 mm diameter (6,000 Nm peak torque) and one type with 660 mm diameter (2,800 Nm peak torque), Fig. 9.

In short, torque motors are at home anywhere traditional gear trains, chains, or timing belts have been used in the past. The most important advantages are maintenance savings (no moving parts subject to wear), energy savings (no power loss in gearings), space savings, reduced noise and vibration, simplified installation.

2.2. Linear driving systems

There are 4 ways to create linear motion:

1. Pneumatic/hydraulic. A pneumatic or hydraulic system is often recommend when high forces are needed. Accurate motion control is difficult, especially at high speeds and high accuracy.

2. Belt. At velocities of approximately 1 m/s, a belt is often used. A disadvantage of the belt is lack of stiffness. The accuracy is in the range of several 100 microns.

3. Ball screw. A ball screw transfers a rotation (stepper or servo motor) into linear motion. Typical application areas are velocities < 1 m/s, with accuracies around several microns. Recent applications and achievements of the three systems in machine tools are widely shown in [16].

4. Linear motor. The linear motor is ideal for high speed (from 1 to 10 m/s) in combination with high accuracy (from 1 till 10 microns). Another important benefit is the short positioning time – Fig. 10.

2.2.1. Linear electric motor

Linear electric motors work on different principles (Fig. 11). The first solution is to use electrostatic field. A maximum force density of about 16 N/m^2 can be obtained. The second way is to use electromagnetic field. The third and fourth solutions are based on piezoelectric and magnetostrictive properties of different materials. The force developed by these two motors can be very high but the stroke is very small [18] – Table 1.

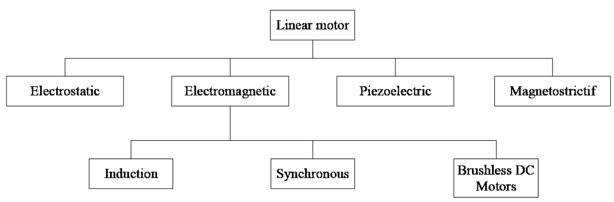

Fig. 11. Linear motor classification.

Table 1

Rated force range for linear motors, continuous duty, natural cooling

Induction linear motor	1–2 N/cm^2
Slotted permanent magnet synchronous motor	< 6 N/cm^2
Slotless permanent magnet synchronous motor	<3 N/cm^2
Reluctance motor	1.5 N/cm^2
Transverse flux motor	3 N/cm^2
Piezoelectric motor	depending on configuration
Magnetostrictiv motor	depending on configuration
Electrostatic motor	16 N/m^2

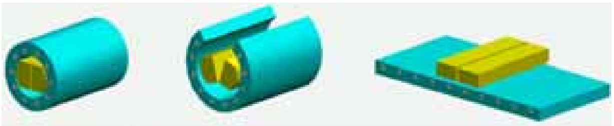

Fig. 12. Transformation of a rotative motor in a flat linear motor.

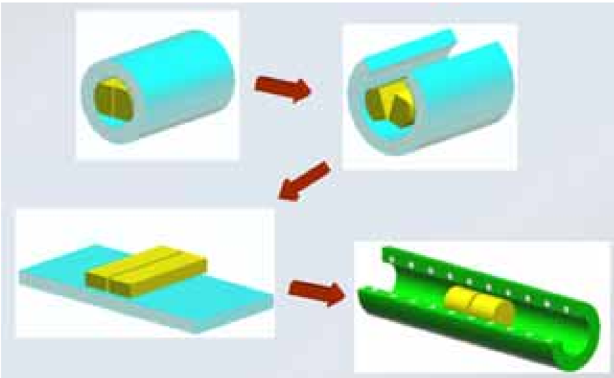

Fig. 13. Transformation of a rotary motor in a tubular linear motor.

The linear motors have two parts: the primary and the secondary. There is no mechanical contact between them. They work as rotative motor. One armature, named ″rail″, ″tracker″ or ″ruler″ is longer and it is fixed. The shorter armature is named ″slider″ or ″forcer″.

The imaginative transformations of a rotary motor in a linear flat motor and in a tubular linear motor are presented in Figs. 12 and 13.

With this design, the load is connected directly to the motor. Direct linear motion is achieved without any turn of the rotary into the linear one.

Electromagnetic motors can be divided in three main groups: induction motors, synchronous motors and DC motors. The main difference between them is the excitation mode, which is generally produced by magnets except for the induction motor where it is self-induced. The difference between a DC motor and a synchronous motor consists in the supply part.

The former generates a trapezoidal electro magnetic force (emf) waveform and is supplied with a rectangular phase current. It is generally controlled like a motor with brushes, since a position sensor produces commutating DC-currents in the stator winding, based on the position of the magnetic poles. On the other hand, the synchronous motor produces a sinusoidal emf waveform and is supplied with a sine wave phase current.

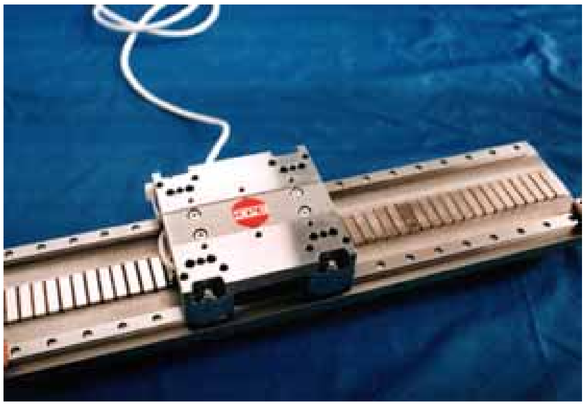

Fig. 14. Flat synchronous linear motor [4].

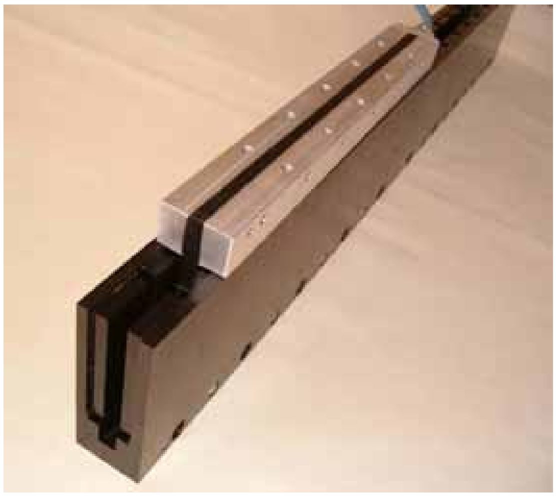

Fig. 15. Slotless linear motor [4].

Fig. 16. Tubular linear motor [4].

Different configurations of linear motors are presented in Figs. 14, 15 and 16.

Less than a decade ago, it was a difficult task to find a commercially available linear bearing that could reach 5 m/s at a demanding straightness, load capacity and stiffness [17]. Today there are many linear bearings with these attributes and they are fairly cost effective. Advancements in linear encoder technology allow higher speed operation, too. Today’s linear encoders and other devices are able to meet this challenge, are less noisy and cost less.

Improvements in linear, mechanical drives have also moved forward. Ball screws with higher accuracy and larger leads result in higher throughput. Timing belts have high repeatability and speeds of well over 5 m/s. Both of these technologies have historically solved motion control applications, and will continue to do so. However, neither of these provide the speed and accuracy combination required by an increasing number of today's motion applications.

More and more we are facing with the higher accuracy, higher speed applications to solve this, the driving system must be able to respond faster, have less wear and have extremely high resolution capabilities. A device that can provide this does exist. It is the brushless linear motor.

2.2.2. Linear motor features

Advantages:

High speeds. The maximum speed of a linear motor is limited only by the bus voltage and the speed of the control electronics. Typical speeds for linear motors are 3 m/s with 1 micron resolution and over 5 m/s, with coarser resolution.

High precision. The accuracy, resolution, and repeatability of a linear motor driven device are controlled by the feedback device. With the wide range of linear feedback devices available, resolution and accuracy are primarily limited to budget and control system bandwidth.

Fast response. The response rate of a linear motor driven device can be over 100 times higher than that of a mechanical transmission. This means faster accelerations and settling times, thus higher throughput.

. *Stiffness*. Because there is no or simple mechanical linkage, increasing the stiffness could be simply a matter of gain and current. The spring rate of a linear motor driven system can be many times higher than that of a ball screw driven device. However it must be noted that this is limited by the motor peak force, the current available and the resolution of the feedback.

Zero backlash. Without or with simple mechanical transmission components, there is no backlash, except one generated by rotations around co-ordinate axes. Resolution considerations do exist. That is the linear motor must be displaced by 1 feedback count before it will begin to correct its position.

. *Maintenance free operation*. Because the linear motors of today have no contacting parts there is no wear.

Disadvantages:

. *Cost*. Linear Motors are expensive. This is due to the relative low volume produced, and the price of magnets. Since most linear motor designs mount rare earth magnets to the length of the rail, and the cost of these magnets is high, long travel motors become expensive. However as the popularity of linear motors continues, volume will rise and cost will decline. This process has begun. Linear feedback must also be considered in the cost of using a linear motor. Most importantly, if system accuracy requires linear encoder feedback, the cost difference between linear and rotary technology is greatly reduced.

Table 2

Comparison of driving systems

Best 1 2 3 4 5 Worse

Drive technology by comparison	Ball screw	Rack end pinion	Linear motor
Feed rate	3	2	1
Acceleration	3	2	2
Surface quality	2	2	2
Noise level	4	2	2
Power requirement	3	3	4
Safety at loss of power	2	2	4
Life-time	3	2	2
Collision sensitivity	3	2	2
Easy service design	3	2	4
Investment costs	2	3	5
Repair costs	3	2	4
Economic efficiency	2	2	3

. *Higher bandwidth drives and controls*. Since there is no or few mechanical links between the motor and the load, servo response, bandwidth, must be faster. This includes higher encoder bandwidth and servo update rates.

Force per package size. Linear motors are not compact force generators compared to a rotary motor with a transmission offering mechanical advantage. For example to produce even 65 N of continuous force, a linear motor's cross section is approximately 50 mm x 40 mm. Compare this to the cross section of a 10 mm diameter ball screw which produces 450 N of thrust and one can see that linear motors are not mighty devices.

. *Heating*. In most linear motor applications, the forcer is attached to the load. Any Joule losses are then directly coupled to the load. If an application is sensitive to heat, thermal management techniques need to be applied. Air and water cooling options are popular and common.

. *No (minimal) friction*. This may not sound like a problem, but it certainly can be. For instance, a linear motor is traveling at 3 m/s and loses power. Without some resistance in the system, it does not take long before the motor reaches the end of stroke and mechanical stops.

An interesting and quit complete comparison of the three driving systems is shown in Table 2 [17].

Now there are many companies who produce linear motors: Etel, Siemens, Phase Motion Control, Anorad, Baldor, Baumueller, Tecnotion, Yaskawa, Parker, Aerotech, Kollmorgen, Copley Controls, etc.

2.2.3. Requirements for applications

Linear motors cannot function on their own. Before motion can occur, a platform must be engineered to provide support, direction, and feedback for the linear motor. Structures, bearings, cables, connectors, encoder, travel stops, homing sensor and other components must be performance matched and integrated to achieve desired motion and control. In Fig 14, the linear motor magnet rail is mounted on a stationary base and the

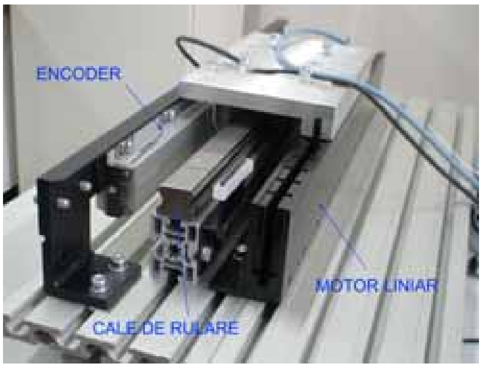

Fig. 17. Positioning system with slotless linear motor [4].

forcer is mounted to the moveable carriage. High precision rail bearings connect the carriage to the base, providing load support, low-friction translation, and precise linear direction. A high resolution linear encoder, with scale mounted on the base and reading head on the carriage, provides the required velocity and positional information to the motor controller. Unlike screw driven tables, the only contact between the moving carriage and the stationary base is through the linear support bearings.

3. ACHIEVEMENTS

There are already many applications of the linear motors:

- Machine tools - milling and grinding machines.
- Precision machining – laser cutting, engraving, substrate dicing, point diamond turning, micro machining.
- Electronic assembly & test – ATE, bonders, vision alignment, component testing.
- Metrology – CMM, AOI, surface measurement, vision inspection.
- Semiconductor – photolithography, FPD inspection
- Life sciences – liquid handling & delivery, micro plate robotics.
- Constant velocity image scanning & large format printing.
- Handling systems.
- Packaging machines.

3.1. Machine tools

A trunnion table - a rotary table in combination with an oscillating one - having two numerically controlled axes, is driven on the both axis by torque motors. They don't exist any connecting elements between motor and rotating assembly (see above Fig. 6).

3.2. Elevators

Mitsubishi developed in 1999 the first gearless motor for elevators. In order to reduce space they developed in 2001 the slim traction motor. The motor's rotor has been given a hollow cylindrical form and this allows the inner surface to be used for an internal expanding double brake. Moreover, the encoder has been installed within the space inside the brake mechanism. Then, by integrating the rotor and sheaves within the unit itself, and by dispensing with coupling parts, the dimensions of the equipment were reduced and reliability was raised – Figs. 18 and 19 [6].

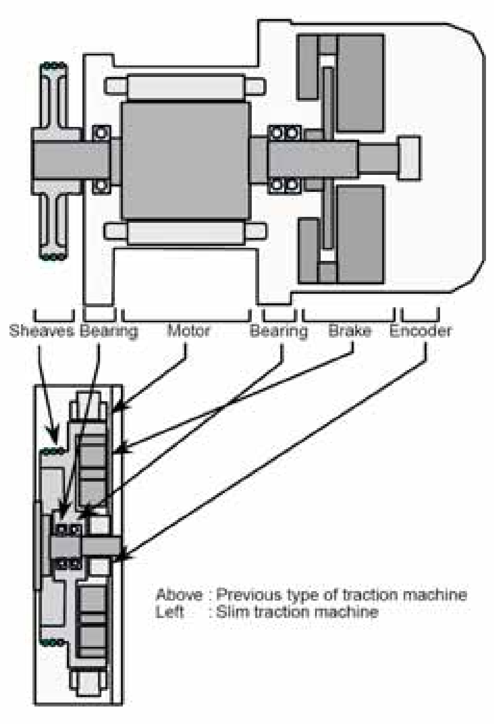

Fig. 18. Comparative structure of traction machines [6].

The benefits of permanent magnet, ac synchronous, gearless lift motors are numerous.

The design reduces the need for maintenance when compared to a geared solution but most important offers increased level of efficiency necessary in today's environment.

They are changing the way that many people in the industry feel about lift drive systems.

Comparing with solution with asynchronous motors, the advantages are:

- smooth functioning due to lower speed,
- weight and volume are reduced,
- easier maintenance,
- better efficiency,
- lower noise.

Usually, the construction is with radial field, but Kone [19] (Fig. 20) uses axial field motors. Examples for other producers are: Otis, Schindler, Leroy-Somer, Hyundai, Hitachi, Bravo, etc.

Fig. 19. External view of slim traction machine Mitsubishi – 3.7 kW.

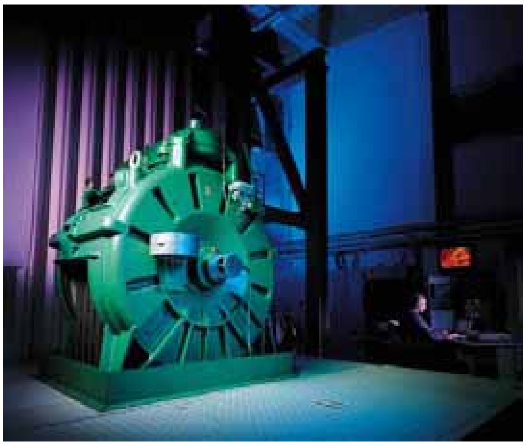

Fig. 20. Axial field motor – Kone.

4. CONCLUSIONS

By acquiring grater and grater knowledge - both by the motor building specialists and by complex systems designers - the use of the direct driving systems will be continuously widened. The advantages of this quite new technology will impose it in many areas of science and technology. The full profit could be reached on the condition that proper measures are taken and suitable connecting components will be used. An open dialog among specialists is compulsory.

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