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STUDIES ON THE POSSIBILITY OF USING LINEAR MOTORS IN DRIVE OF THE MACHINE TOOLS

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Abstract: Linear drive technologies are steadily expanded in various applications, especially in industry, where high precision electrical direct drive systems are required. This paper analyzes the advantages of using linear motors in kinematic chains of machine tools.

1. INTRODUCTION

The linear electric motors can be used in machine tools in the feed kinematic chain driving. Among their advantages there are: higher feed and positioning speeds increasing also machining rates, increased efficiency, constructive simplicity which improves servo accuracy by eliminating gear related mechanical problems, better rigidity. The existent linear electric motors can enable forces up to 20 000 N and speeds greater than 400 m/min. Their working mode is presented in Fig. 1. On the bed 1, the guides 2 and secondary of the linear motor are rigidly attached. The linear motor primary is fixed on the saddle 5. For system assurance there are the closing plates 6 [1].

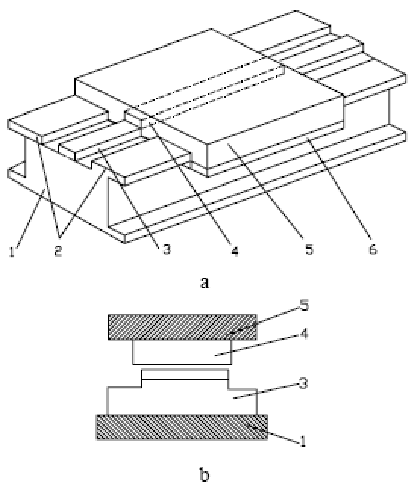

Fig. 1. Working mode of the linear electric motors.

In applications of linear motors in machine tools, we need to utilize the high speed and high response direct drives for machining. The servo control must achieve as high as possible tracking performance together with a good dynamic stiffness for maintaining machining stability and reducing the effect of machining disturbance forces on the tool position.

2. TYPES OF LINEAR MOTORS

The linear motor was invented by Professor Eric Laithwaite, the British electrical engineer who died on 6 December 1997, aged 76. It projected a shuttle across a weaving loom using a linear motor. Professor Laithwaite had been fascinated with the weaving process ever since his boyhood spent in Lancashire, the UK's home of textile manufacture.

Professor Laithwaite described his invention as “no more than an ordinary electric motor, spread out”. The principle created magnetic fields on which an object rested and travelled without being slowed by friction. This magnetic levitation had long been understood, but it was Laithwaite who pioneered the commercial development of the first practical applications, developing direct linear drives for both machinery and transport.
Linear motors have evolved in several guises but perhaps the most commonly encountered are tubular types, flat or “U” channel types, which are finding increasing use thanks to their low profiles and high output. For all intents and purposes, and for the purposes of this book, we can assume most linear motors, for motion control, use brushless technology.
We’ve already heard Professor Laithwaite’s description of a linear motor as a rotary motor rolled out flat.
The forcer (rotor) is made up of coils of wires encapsulated in epoxy and the track is constructed by placing magnets on steel. The forcer of the motor contains the windings, hall effect board, thermistor and the electrical connections. In rotary motors, the rotor and stator require rotary bearings, to support the rotor, and maintain the airgap between the moving parts. In the same way linear motors require linear guide rails which will maintain the position of the forcer in the magnetic field of the magnet track. At the same time rotary servo motors have encoders mounted to them, to give positional feedback of the shaft. Linear motors need positional feedback in the linear direction and there are many different linear encoders on the market today. By using a linear encoder, position is directly measured from the load and this again increases the accuracy of the position measurement.
The control for linear motors is identical to rotary motors. Like a brushless rotary motor, the forcer and track have no mechanical connection; i.e., no brushes. Unlike rotary motors, where the rotor spins and the stator is held fixed, a linear motor system can have either the forcer or the magnet track move.
Most applications for linear motors, at least in positioning systems, use a moving forcer and static track, but linear motors can also be used with a moving track and static forcer. With a moving forcer motor, the forcer weight is small compared to load. However, there is the need for a cable management system with high flex cable, since the cable has to follow the moving forcer. With a moving track arrangement, the motor must move the load plus the mass of the magnet track. However, there is the advantage that no cable management system is required. Similar electromechanical principles apply whether the motor is rotary or linear. The same electromagnetic force that creates torque in a rotary motor also does so in the linear counterpart.
Hence, the linear motor uses the same controls and programmable positioning as a rotary motor. In a rotary motor, torque is measured in Nm and for the linear motors force in N. Velocity is measured in rev/min for the rotary and m/sec for linear motors. Duty cycles are measured in the same way for both types of motor.
Looking at the various motor types, we see that a linear motor directly converts electrical energy to linear mechanical force and is directly coupled to the load. There is no compliance or windup, and higher accuracy and unlimited travel are achieved. Today, linear motors typically reach speeds of 5m/sec, with high accelerations of 5g in practice.
Theoretically motors can reach over 20g with 40m/sec velocity, however bearings and required motion parameters de-rate this performance somewhat. There is no wear, no lubrication and therefore minimal or no maintenance cost. Finally, there is higher system bandwidth and stiffness, giving better positional repeatability and accuracy as well as higher speed.

A linear motor can be flat, U-channel, or tubular in shape. The configuration that is most appropriate for a particular application depends on the specifications and operating environment.

2.1. Cylindrical moving magnet linear motors

In these motors (fig. 2), the forcer is cylindrical in construction and moves up and down a cylindrical bar which houses the magnets. These motors were among the first to find commercial applications, but do not exploit all of the space saving characteristics of their flat and U channel counterparts. The magnetic circuit of the cylindrical moving magnet linear motor is similar to that of a moving magnet actuator.
The difference is that the coils are replicated to increase the stroke. The coil winding typically consists of three phases, with brushless commutation using Hall effect devices.
The forcer is circular and moves up and down the magnetic rod. This rod is not suitable for applications sensitive to magnetic flux leakage and care must be taken to make sure that fingers do not get trapped between magnetic rod and a attracted surface. A major problem with the design of tubular motors is shown up when the length of travel increases. Due to the fact that the motor is completely circular and travels up and down the rod, the only point of support for this design is at the ends. This means that there will always be a limit to length before the deflection in the bar causes the magnets to contact the forcer.

Fig. 2. Cylindrical moving magnet linear motors

2.2. U Channel Linear motor

This type of linear motor (fig. 3) has two parallel magnet tracks facing each other with the forcer between the plates. The forcer is supported in the magnet track by a bearing system.

Fig. 3. U Channel Linear motors

The forcers are ironless, which means that there is no attractive force and no disturbance forces generated between forcer and magnet track. The ironless coil assembly has low mass, allowing for very high acceleration. Typically, the coil winding is three phase, with brushless commutation. Increased performance can be achieved by adding air cooling to the motor. This design of linear motor is better suited to reduced magnetic flux leakage, due to the magnets facing each other and been housed in a ‘U’ shaped channel. This also minimises the risks of being trapped by powerful magnets. Due to the design of the magnet track, they can be added together to increase the length of travel, with the only limit to operating length being the length of cable management system, encoder length available and the ability to machine large flat structures.

2.3. Flat type linear motors

There are three design types of these motors: *slotless ironless, slotless iron*, and *slotted iron.* Again, all types are brushless. To choose between these types of motor requires an understanding of the application.

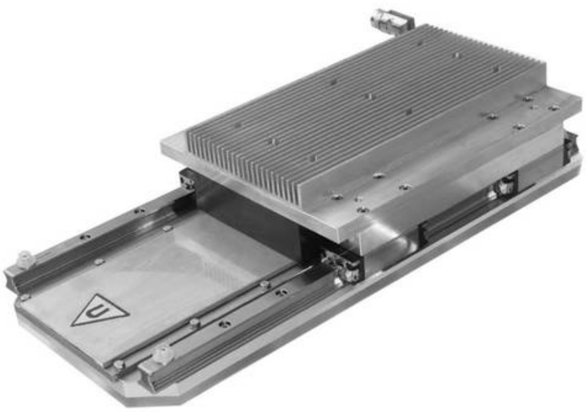

Fig. 4 . Flat type linear motor

The following is a list of the main characteristics of each type of motors.

2.3.1. Slotless Ironless flat motors.

The slotless, ironless flat motor is a series of coils mounted to an aluminum base. Due to the lack of iron in the forcer, the motor has no attractive force or cogging (the same as U-channel motors). This will help with bearing life in certain applications. Forcers can be mounted from the top or sides to suit most applications.

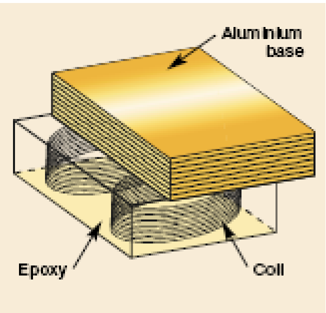

Fig 5. The constrution of Slotless Ironless flat motors

Ideal for smooth velocity control, such as scanning applications, this type of design yields the lowest force output of flat track designs. Generally, flat magnet tracks have high magnetic flux leakage, and as such, care should be taken while handling these to prevent injury from magnets trapping you between them and other attracted materials.

2.3.2. Slotless Iron flat motors

The slotless, iron flat motor is similar in construction to the slotless ironless motor except the coils are mounted to iron laminations and then to the aluminum base. Iron laminations are used to direct the magnet field and increase the force.

Due to the iron laminations in the forcer, an attractive force is now present between the forcer and the track and is proportional to force produced by the motor. As a result of the laminations, a cogging force is now present on the motor. Care must also be taken when presenting the forcer to the magnet track as they will attract each other and may cause injury.

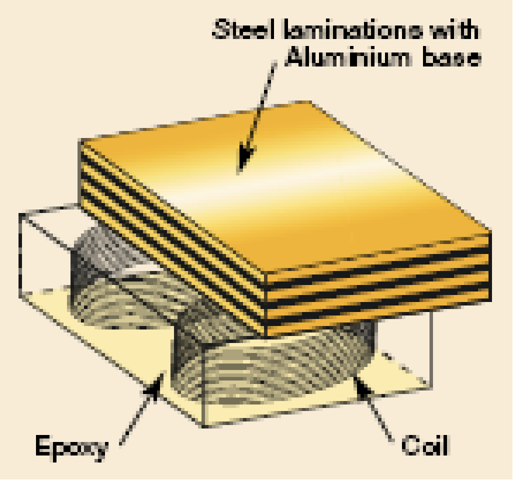

Fig 6. The constrution of Slotless Iron flat motors

This design of motor produces more force than the ironless designs.

2.3.3. Slotted Iron flat motors

In this type of linear motor, the coil windings are inserted into a steel structure to create the coil assembly. The iron core significantly increases the force output of the motor due to focusing the magnetic field created by the winding. There is a strong attractive force between the iron-core armature and the magnet track, which can be used advantageously as a preload for an air bearing system, however these forces can cause increased bearing wear at the same time. There will also be cogging forces, which can be reduced by skewing the magnets.

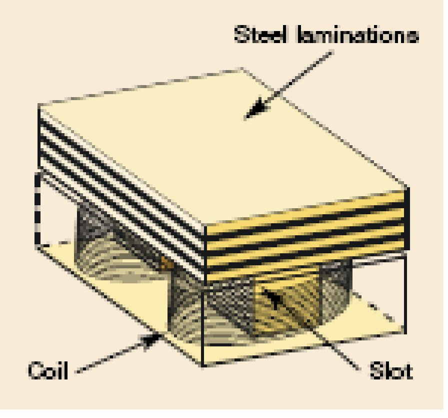

Fig 7. The constrution of Slotted Iron flat motors

3. THE BENEFITS OF LINEAR MOTORS

In the following sections, we compare the performance and cost of various translational mechanics including belt and pulley, rack and pinion and leadscrew, to a U channel brushless linear motor.

3.1. Linear motor vs belt and pulley

A popular way to produce linear motion from a rotary motor, the belt and pulley system typically has its thrust force capability limited to the tensile strength of the belt. At the same time, accuracy and repeatability suffer from the inherent limitations of the belt travel system.

For example: A belt and pulley system comprising a 100mm diameter pulley and a 5:1 gearbox could produce 3.14 m/sec of linear motion, with the motor's input speed at 3000rev/min. The theoretical resolution of this system with a 10,000 PPR (pulses per revolution) encoder through the gearbox would be 6.3 μm. However, positioning a load on a belt through a 5:1 gearbox to 6.3 μm in any repeatable manner is practically impossible.

Mechanical windup, backlash and belt stretching would all contribute to inaccuracies in the system. The fact that the measuring device (rotary encoder) is really measuring the motor shaft position, and not the actual load position, also contributes to inaccuracy. A second linear encoder could be used to measure the actual load position, but this would add more cost and require a special servo setup, so that position can be achieved quickly. Settling time is also a problem with belt systems. Even the best reinforced belts have some compliance when positioning ±1 encoder counts. This compliance will cause a ringing, or settling delay, at the end of a very quick move, making it impossible to push the machine to a higher throughput.

This problem worsens with longer belts. The best that can be achieved in a belt and pulley system in terms of positioning repeatability is around 25 to 50 μm. Since both speed and repeatability is the name of the game when it comes to servo mechanisms, the belt and pulley system is not a good choice for high speed, high accuracy machines.

On the other hand, a linear system can reach speeds of 10m/sec and position the load to within 0.1 μm, or better. Only the resolution of the linear encoder used and the stability of mechanics limit the performance. Since there is no backlash or windup, a direct drive linear motor system will have repeatability to one encoder count over and over again.

Settling time is also unchallenged, since the load is directly connected to the moving forcer coil and there is no inherent backlash in the linear motor system. The encoder is also directly connected to the load to keep the positioning accuracy where it really matters. All this adds up to the shortest settling times achievable and high performance within an encoder count.

Even in long travel linear motor systems, performance and accuracy remain undiminished, since magnet tracks are stackable and the load remains directly connected to the forcer. At the same time, with thrust limited for the belt and pulley systems, loads have to be light. Conversely, a typical linear motor can produce several thousand Newtons of thrust force and still not compromise performance.

3.2. Linear motor vs rack and pinion

The rack and pinion system is mechanically stiffer than a belt and pulley but the same translational equations apply. So, a 100mm pinion gear through a 5:1 gearbox could produce a 3.14m/sec linear speed at 3000rpm, although rack and pinion provides more thrust capability. Once again, the lack of accuracy and repeatability is the major drawback.

The gearbox and pinion gear will have bi-directional inaccuracies and, over time, wear will increase the problem.

As with the belt and pulley system, backlash in the system prevents the encoder on the motor from detecting the actual load position. The backlash in the gears not only leads to inaccuracy but also causes instability in the servo system, forcing lower gains and slower overall performance.
Linear motors do not encounter such system limitations and can push a machine to greater speeds. Even as the mechanics wear over time, the direct-coupled linear motor and encoder will always provide the most accurate positioning.

3.3. Linear motors vs screw systems

Probably the most common type of rotary to linear translational mechanics is the screw, which includes both leadscrews and ballscrews.
The leadscrew system, though inexpensive, is an inefficient way of producing linear motion, typically less than 50 per cent of the output. It is also not a good choice for high duty cycle applications, as the nut which rides the screw suffers from wear due to the friction interface. Furthermore, positional accuracy and repeatability is a problem, as the screw is typically not precision made and has inherent inaccuracies.
The resulting high friction may minimise backlash but produces heat and wears, reducing accuracy and repeatability.
The ballscrew system uses a ball nut in the screw and is therefore much more efficient at converting rotary motion to linear motion, at typically 90 percent oF the output. This type of screw system outperforms the leadscrew for high duty cycles. A precision ground ballscrew will improve accuracy, but is costly, and, over time, will still wear and result in reduced accuracy and repeatability.
Either way, whether leadscrew or ballscrew, the basic screw system cannot achieve high linear speeds without a compromise on system resolution. It is possible to increase the speeds of a ballscrew by increasing the pitch (ie 25mm/rev), however this directly effects the positional resolution of the screw. Also too high a rotational speed can cause a screw to whip or hit a resonant frequency, causing wild instability and vibration. This problem is magnified as the length of the screw increases. This obviously limits the ability to increase a machine’s throughput, or increase travel while maintaining positional resolutions.
When compared with a screw, the linear motor system does not introduce any backlash or positioning problems with the feedback device, as the linear slide bearing is its only friction point.
As with all the other translation systems discussed, the positioning of the load in a screw system is made with a rotary encoder mounted on the motor. The controller never really closes a loop at the load. In a linear motor system the encoder is at the load and is truly being positioned.

4. CONCLUSIONS

Let us consider the feed kinematic chain having as transformation mechanism a ball screw-nut mechanism as figure 8 shows.

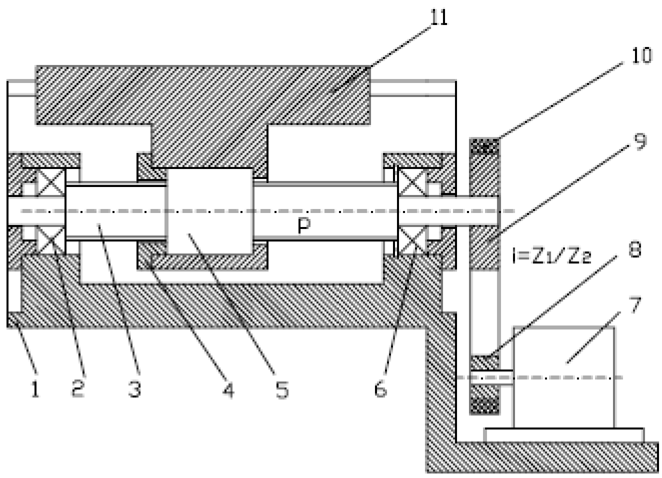

Fig. 8. Feed system driven a by linear electric motors

On the bed 1, on the bearings 2 and 6, the ball screw 3 is mounted. The electric motor 7 drives the ball screw (with pitch *p*) through a reduced composed by the pulleys 8 and 9 and a toothed belt 10. The nut 5, by means of support 4, displaces the slide 11 on the machine guides [2].
In case of replacing this system with one having a linear electric motor, the components mechanisms ball screw-nut, nut support, reducer and rotary electric motor are removed. The achieved mechanical structure is schematically presented in figure 9.

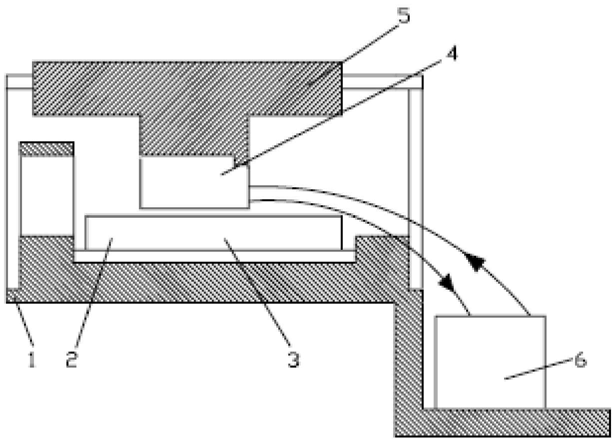

Fig. 9. Mechanical structure with linear electric motor

On the bed 1, the secondary is mounted, being formed in this case by two elements 2 and 3. The primary 4 is fixed on the saddle 5. The relative motion between primary and secondary leads to the properly positioning of the saddle. For motor cooling there is a special system 6.
The electric motors represent a modern solution for driving the feed and positioning kinematic chains in new and refabricated machine tools. By using these motors, the construction of the feed system is simplified by removing the rotary electric motor, couplings, mechanism for motion transformation (generally ball screw−nut), and eventual speed reducers. Nowadays, there are linear electric motors that cover a great range of speeds having also some limitations regarding the developed forces. It is recommended their using in small and medium machines, existing the perspective of using them even in heavy machine tools.

It is strongly recommended the realization of a complete calculation from the static and dynamic point of views, on the basis of the technical documentation supplied by the motor producers. The cooling systems specific to these types of driving will be treated also carefully.

Before the advent of practical and affordable linear motors, all linear movement had to be created from rotary machines by using ball or roller screws or belts and pulleys. For many applications, for instance where high loads are encountered and where the driven axis is in the vertical plane, these methods remain the best solution. However, linear motors offer many distinct advantages over mechanical systems, such as very high and very low speeds, high acceleration, almost zero maintenance (there are no contacting parts) and high accuracy without backlash. Achieving linear motion with a motor that needs no gears, couplings or pulleys makes sense for many applications, where unnecessary components, that diminish performance and reduce the life of a machine, can be removed.

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