Proceedings of the International Conference on Manufacturing Systems – ICMaS
Vol. 4, 2009, ISSN 1842-3183
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FABRICATION AND REFABRICATION OF MACHINE TOOLS. LINEAR ELECTRIC MOTORS USED IN FEED/POSITIONING KINEMATIC CHAINS

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Abstract: *In this paper some specific aspects regarding fabrication and refabrication of feed kinematic chains of classical machine tools especially of CNC machine tools. The linear electric motors represents a modern solution, used increasingly by companies specialized in machine tools fabrication and refabrication. Starting from the mechanical structures of the new or old machines, by using these electric motors some feed systems are obtaining with advanced features in regard with those using rotary electric motors.*

Key words: *machine tools, fabrication, refabrication, feed kinematic chain, linear electric motors, characteristics, operation.*

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 [4].

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.

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 [5].

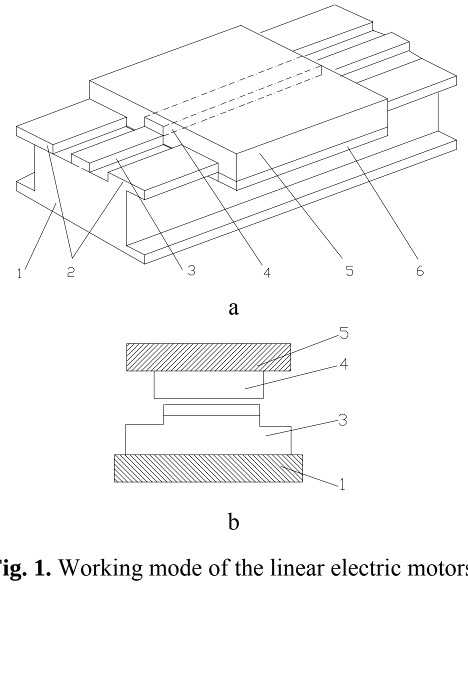

Fig. 1. Working mode of the linear electric motors.

2. FEED SYSTEMS DRIVEN BY LINEAR ELECTRIC MOTORS

Let us consider the feed kinematic chain having as transformation mechanism a ball screw-nut mechanism as Fig. 2 shows.

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.

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 Fig. 3 [1].

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.

For the old structure (Fig. 2), the characteristics of the rotary electric motor are known. They are of the of the type of those presented in Fig. 4 [4].

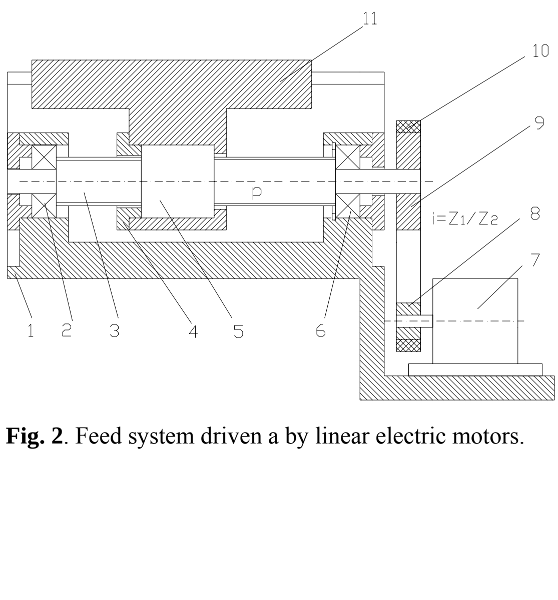

Fig. 2. Feed system driven a by linear electric motors.

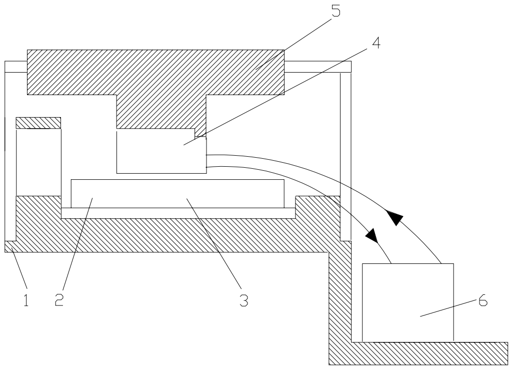

Fig. 3. Mechanical structure with linear electric motor.

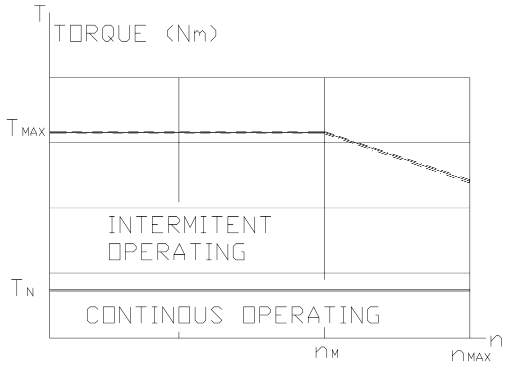

Fig. 4. Rotary electric motor characteristics.

The specific characteristic of the feed kinematic chains of the machine tools is that the feed motions, having low speeds deriving from the technological requirements, take more time than the positioning motions (with great speed resulting from productivity requirements).

Taking in consideration in case of refabrication, that the running in the initial case was properly, for the subsequent calculation the following values are important (shown in Fig. 4): n_{MAX} – maximum speed (rpm); T_N – rated torque (Nm); T_{MAX} – admissible maximum torque for a short time (Nm); n_M – speed from which slipping is present (rpm).

On the basis of these values resulted from the motor characteristic, one can determine:

- maximum speed:

$$v_{MAX} = n_M \cdot i \cdot \frac{p}{1000} \text{ [m/min.]}, \qquad (1)$$

- force developed by the feed kinematic chain (at rated toque):

$$F_{MAX} = T_N \cdot \frac{1}{i} \cdot \frac{2 \cdot \pi}{p} \cdot 1000 \text{ [N]}. \qquad (2)$$

In the previous relations we have also: i – transfer ratio of the reducer ($i < 1$) [-], and p – ball screw spindle pitch [mm].

The characteristics of the electric motors used for the feed kinematic chains of the machine tools are of the type shown in Fig. 5, where: F_{MAX} – maximum force [N]; F_N – rated force [N]; v_{MAX1} – maximum speed at maximum force; v_{MAX2} – Maximum speed.

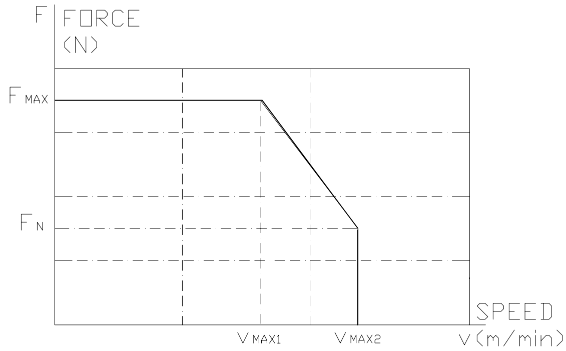

Fig. 5. Feed kinematic chain drive characteristic.

It is recommended the choice of a linear motor (or more than one connected as Fig. 6 shows) so that the following relations to be verified:

$$v_{MAX1} \geq v_{MAx} \qquad (3)$$

$$F_N \geq F_{MAX} \qquad (4)$$

In Fig. 6 three variants are presented: a – two motors in parallel in the same plane; b – two primars on a single secondar; c – two motors in parallel in different planes.

In case of refabrication of a machine tool, after choosing the linear electric motor system it is recommended if possible, the complete verification calculation in static and dynamic regime.

For new machine tools this calculation is done in the design stage, having on the base the documentation supplied by the motor producers.

The electric motor producers supply also for designers calculation programs achieved with their databases. Therefore, after inserting the input data presented above), the characteristics of the form shown in Fig. 7 are obtained.

In Fig. 7 one considered a trapezoidal distribution of the speed for a total stroke of 1 200 mm.

The motor has the characteristic shown in Fig. 8 where the running points for the required speed and force are presented.

3. LINEAR ELECTRIC MOTOR COOLING

The linear electric motors having no fans as the rotary ones, require the existence of a self cooling system. Usually, these motors do not need to work at temperatures greater of 70 °C when the environment temperature is between 0° and 45 °C. The heating characteristic es of the type shown in Fig. 9. The maximum admissible temperature is noted with Θ_{max}. The time constant is T_{th}. It is considered that the temperature is stabilized after a time of ~5 × T_{th}.

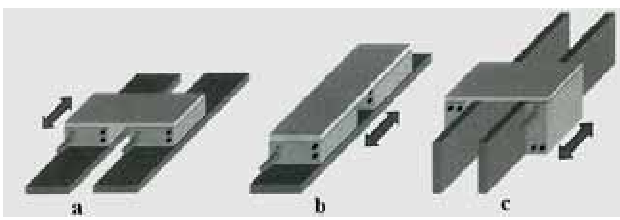

Fig. 6. Variants of linear motors.

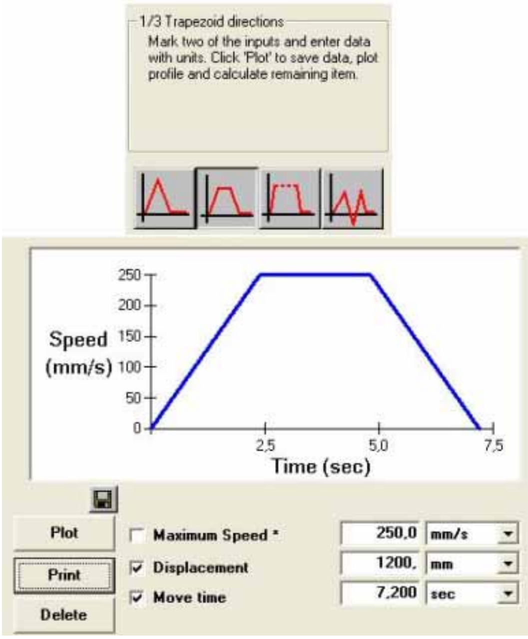

Fig. 7. Trapezoidal distribution of the speed.

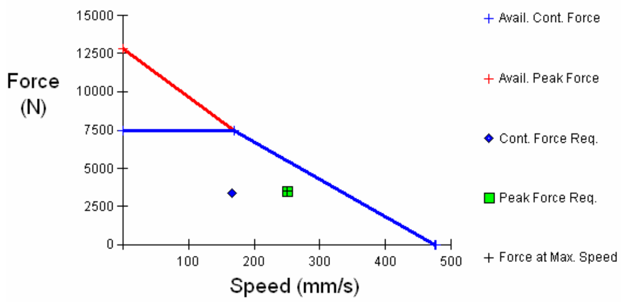

Fig. 8. Linear electric motor chaacterstic.

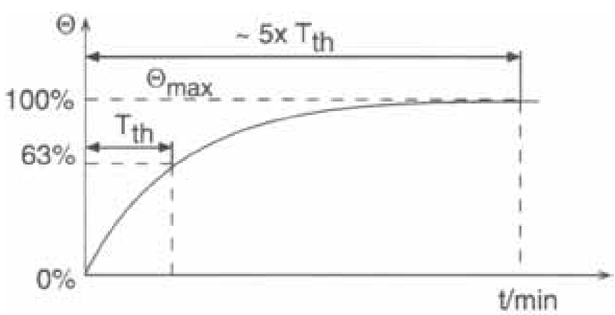

Fig. 9. The heating characteristic.

For cooling these motors, usually the oil is used, which is cooled by means of heat changers presented schematically in Fig. 10.

The oil cooling is achieved with the help of ventilators as in case *a*. The warm air is evacuated in atmosphere. If there is a possibility of using a source of cold liquid \(water), one can use the systems presented in variant *b*. The most efficient cooling systems have refrigerators (variant *c*).

Table 1 shows a comparison between the three type of cooling.

4. EXAMPLE

As an example, we will consider a 1700 kg load that is required to move 6 000 mm in 7.5 s, dwell for 275 ms, and then repeat.

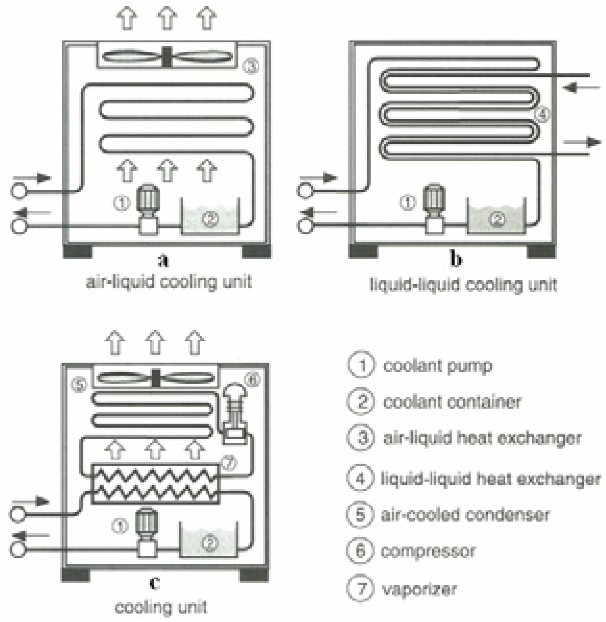

Fig. 10. Heat changers.

Table 1

Comparison between three types of cooling

	Air – to liquid cooling unit	**Liquid-to-liquid cooling unit**	**Cooling unit**
Coolant temperature control accuracy	Low(±5° C)	Low(±5°C)	Good(±1° C)
Superordinated coolant circuit required	No	Yes	No
Heating of ambient air	Yes	No	Yes
Power loss recovery	No	Yes	No
Size of the cooling unit	Small	Small	Large
Dependent of ambient temperature	Yes	No	No
Environment-damaging coolant	No	No	Yes

The first thing for calculating [6] the required forces and size the linear motor is the move characteristics. We need to calculate the peak speed, acceleration, and space for acceleration.

Considering the trapezoidal profile, the total time of the motion is divided equally into 3 parts (acceleration, constant velocity, and deceleration). We obtain the time taken to accelerate: 7.5 s / 3 = 2.5 s.

The peak speed necessary to make the move is.

$$v = \frac{3s}{2t} = \frac{3 \times 6\,\text{m}}{2 \times 7.5\,\text{s}} = 1.2\,\text{m/s} \qquad (3)$$

We now need to calculate the acceleration rate:

$$a = \frac{v - u}{t} = \frac{1.2 - 0}{2.5} = 0.48\,\text{m/s}^2\,. \qquad (4)$$

The distance taken to accelerate the load is:

$$s = ut + \frac{1}{2}at^2 = \frac{1}{2}0.48 \times 2.5^2 = 1.5 \text{ m.} \quad (5)$$

The force required for the acceleration

$$f_a = ma = 1700 \times 0.48 = 816 \text{ N.} \quad (6)$$

The friction force is:

$$f_f = \mu mg = 0.003 \times 1700 \times 9.81 = 50.031 \text{ N.} \quad (7)$$

The peak force is obtained by adding the forces:

$$f_p = f_a + f_f = 816 + 50 = 866 \text{ N.} \quad (8)$$

The RMS force is the average force from the motor and helps determine the final temperature that the coil will reach:

$$f_{rms} = \sqrt{\frac{t_1 f_1^2 + t_2 f_2^2 + t_3 f_3^2 + ... + t_n f_n^2}{t_1 + t_2 + t_3 + ... + t_n + t_{dwell}}} \text{ N,} \quad (9)$$

$$f_{rms} = \sqrt{\frac{2.5 \times 866^2 + 2.5 \times 866^2 + 2.5 \times 866^2}{2.5 + 2.5 + 2.5 + 0.257}} = 851.53 \text{ N.}$$

The RMS force of 851.5 N together with the peak force requirement is used to choose a specific size and model of motor that can apply this force continuously. For this application an Aerotech motor BLMX-502-B with air cooling was chosen (Table 2).

We can now repeat the calculation considering the load forces (cutting force of approx, 150 N) obtaining:

- f_p = 1016 N;
- f_{rms} = 999 N;
- v = 1.2 m/s.

The next step is to determine the coil temperature assuming the environment temperature of 20 °C, which should be added to the coil to get the final coil temperature rise:

Table 2

Linear motor characteristics from catalogue [6]

Parameter	Unit	Value
Continuous force @1.36 bar	N	1186
Continuous force no air	N	816
Peak Force	N	4744
BEMF line-line	V/m/s	**54.33**
Continuous current @1.36 bar	Amp Peak	25.03
Continuous current no air	Amp Peak	17.11
Force Constant, sin drive	N/Amp Peak	**47.38**
Motor Constant	N/√W	**41.20**
Thermal Resistance @1.36 bar	°C/W	0.11
Thermal Resistance no air	°C/W	0.24
Resistance 25°C, line-line	Ohms	1.3
Resistance 125°C, line-line	Ohms	**1.8**
Inductance, line-line	mH	1.0
Max Terminal Voltage	Vdc	320
Magnetic pole pitch	mm	30
Coil Weight	Kg	4.45
Coil Length	mm	502

$$T = R_T \left(\frac{f_{rms}}{M_c} \right) = 0.11 \times \left(\frac{1016}{41.20} \right)^2 = 66.89 \text{ °C} \quad (10)$$

In this application final coil temperature rise will be 86.89 ºC.

The final stage of calculation is to size an amplifier for driving the motor. Firstly we need to check on the current requirement. Also to select the amplifier we need to check for required bus voltage. With the selected amplifier, the maximum speed that could be reached is calculated.

5. CONCLUSIONS

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.

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