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Study of Influence of Permanent Magnets Inclination on Detent Force in Linear Synchronous Motors

***Abstract**. The article presents the results of a study of the impact of permanent magnets inclination for detent force reducing. It will be established in the paper that the minimization of the detent force is achieved by bending the permanent magnets at a certain angle. Based on the results of the magnetic field analysis at different mover positions relative to the track of stator permanent magnets, the force acting on the move is calculated. Its components along Ox axis represent the detent force, and along the axis Oy - the attraction force between permanent magnets and mover ferromagnetic core. The results obtained were confirmed by the motor experimental study.*

***Streszczenie.** Przedstawiono analizę wpływu odchylonej siły magnesu na pracę liniowego silnika synchronicznego. Minimalizacja siły zatrzymywania (utyku, and defent force) jest możliwa przez mocowanie magnesu pod pewnym katem. Obliczono siłę działania pola magnetycznego magnesu. (**Analiza wpływu odchylenia magnesu na siłę zatrzymywania w liniowym silniku synchronicznym**)*

Keywords: Linear synchronous motor, LSDPM, detent force, simulation, FEA, CAD, FEM.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

Intriduction

The article presents the results of a study of the influence of the inclination of permanent magnets (PM) for reducing the detent force. For the purpose of simulation, a 3-D static magnetic field of a linear motor was modeled and analyzed, excited by permanent magnets only in the absence of current in the coil. Based on the results of the magnetic field analysis at different positions of the actuator relative to the path of the stator permanent magnets, the force acting on the motion is calculated. Its components along the Ox axis represent the detent force and along the Oy axis the attraction force between the permanent magnets and the moving ferromagnetic core. The obtained results were confirmed by motor experimental research.

The problem in improving the positioning precision is the large detent force arisen by permanent magnet. We analyzed the static thrust and detent force using FEM (Finite Element Method). Generally, if detent force is enough smaller than static thrust force, high positioning precision can be achieved. We investigated the mechanisms of detent force generation. As the results, we proved that detent force is generated by the thrust caused by the difference between the magnet end and the tooth. We proved that if the width of the permanent magnet is too wide, the total detent force can be estimated by the superposition of each detent force. As the results of the study, we developed the method of design to reduce the detent force of permanent magnet linear synchronous motor. Using the FEA (Finite Element Analysis), this paper investigates two reduction methods of detent force such as adjustment of PM length and skewing. Design criteria to minimize the detent force were obtained. It will be established in the paper that the minimization of the detent force is achieved by bending the permanent magnets [1,2] at a certain angle. Comparisons of reduction effect according to methods and static thrust performance for two topologies are also performed. The detent force is composed of cogging force and end force. By choosing appropriate boundary conditions, the end effect of unit motor model can be ignored. So, the cogging is the main part of the detent force. Essentially, the creation of cogging force is due to the primary slot.

The interactions between permanent magnet poles and the primary pole and slot have changed the air gap permanence between secondary and primary, the magnetic resistance and energy storage of magnetic field have changed with the position of motion, and these changes create thrust ripple. When the motion moves a tooth pitch change occurred periodically, and has no correlation with the armature current.

LSDPMs [3,4,5,6] are characterized by high power density, low heat losses, high dynamics, high positioning accuracy and simplicity in their mechanical construction. But they have one major disadvantage due to the ripple of the motor force, as we said, due to the presence of two additional forces.

The first of these can be called "switching power" and occurs due to the presence of higher harmonics in current and voltage, due to the power supply of the coils from the semiconductor inverters and the unequal magnetic conductivity in the air gap.

The second force is created by the pull between the permanent magnets and the ferromagnetic core of the movable part. This force seeks to maintain the position of the movable part with respect to the permanent magnets and is called the holding force. Other causes of this deleterious force are the limited length of the movable part, the associated "edge effects" and the presence of the teeth of the ferromagnetic core. For these reasons, retention force can be considered as being made up of two ingredients - one *Fend* caused by edge effects and the other Fslot caused by the presence of teeth and channels.

This second ingredient, *Fslot*, is similar to the "cogging" moment in rotating permanent magnet electric machines and depends solely on the geometry and physical structure of the engine. It impairs the control and management of the LSDM at low speeds, as well as the positioning of their moving part. Therefore, limiting the holding force is a very important task in the design of linear permanent magnet synchronous motors. In this regard, this publication discusses one way of limiting it to the design and construction of a particular linear servomotor.

Detent force of slotted LSDPM is due to the interaction between the edges of the permanent magnet and the teeth of the primary core. This paper deals with detent force reduction methods such as adjustment of magnet length and skewing. Reduction effect of detent force and thrust performance for two topologies are also compared.

The detent force plays an important role in the thrust ripple in LSDPM. And these force pulsations contribute to vibrations and acoustic noise of LSDPM. Especially at low speed operation, the ripple can cause resonance, which affects operation performances of the system. So the effect must be reduced in driving system. There are many approaches to improve the detent force profile. One approach is to choose suitable control strategy. Another approach is to modify the structure of motor. This research makes an attempt to improve the force profile by the geometry modifications approach which is to provide pole shoes on the primary poles.

There are various ways to limit and reduce the amount of restraining force [8]. They can be combined depending on whether they relate to the design of the engine or to its operation. This section will look at the part of them related to its construction, which may be called "design measures" to reduce the amount of retention force by changing the magnetic conductivity of the air gap. In the part of linear motors in which the permanent magnets are located, these measures refer to the use of a precisely defined ratio between the magnitudes of the pole and the channel division [1], the change in the width of the permanent magnets and the distances between them, the bevelling of the arrangement of the permanent magnets [2], use of permanent magnets with special shape, etc.

Modelling LSDPM

The object of study in the present work is a flat type LSDPM with a ferromagnetic core shown in Fig. 1. Its technical parameters are given in Table 1. Fig. 2 shows the output three-dimensional CAD model of a linear engine. How Fig. 2 shows, it is clear that the teeth of the core do not have crowns and are the same width along the entire length. In this way, greater workmanship is achieved when concentric coils are made, and their coils are clamped on the tooth and then poured with epoxy resin to achieve mechanical strength.

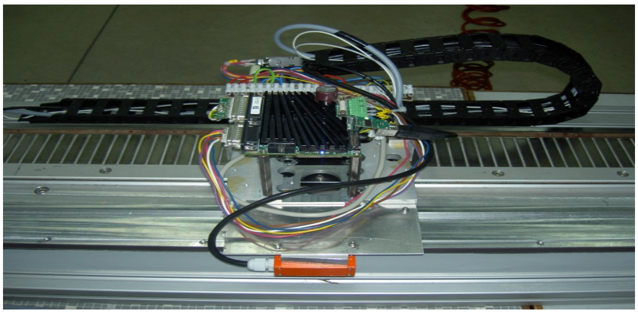

Fig. 1 General view of a linear servomotor.

Table 1 Technical parameters of SLDPM

№	Components	Value
1.	Number of phases	3
2.	Number of poles	10
3.	Number of channels	12
4.	Nominal phase voltage, V	70
5.	Magnetic induction in the teeth and yoke of the core, T	1,6
6.	Dimensions of permanent magnets, mm	76,2/12,7/6,35
7.	Air gap, mm	1
8.	Pole partitioning, mm	15
9.	Channel partitioning, mm	12,5
10.	Nominal phase current, A	5,3
11.	Motor Power, N	185
12.	Speed, m/s	3
13.	Weight of the movable part, kg	6,0
14.	Efficiency	0,6
15.	Power factor	0,9

The magnetic system of the engine has a complex construction and is made of magnetic materials characterized by a strong nonlinearity in their magnetic characteristics.

This complicates the analytical calculation of the holding force. Its calculation can be best done using the finite element method (FEM). When there is no current in the motor windings, the component of the force on the Ox axis acting on the movable part is precisely this force. It is calculated for different positions of the movable part relative to the permanent magnets.

When the permanent magnets are positioned at a certain angle to the axis of the motor, the task of analyzing the magnetic field becomes three-dimensional. Therefore, in this work, the three-dimensional magnetic field of the motor is modeled and analyzed. The magnetic field modeling of a linear motor is based on the Maxwell equations in differential form.

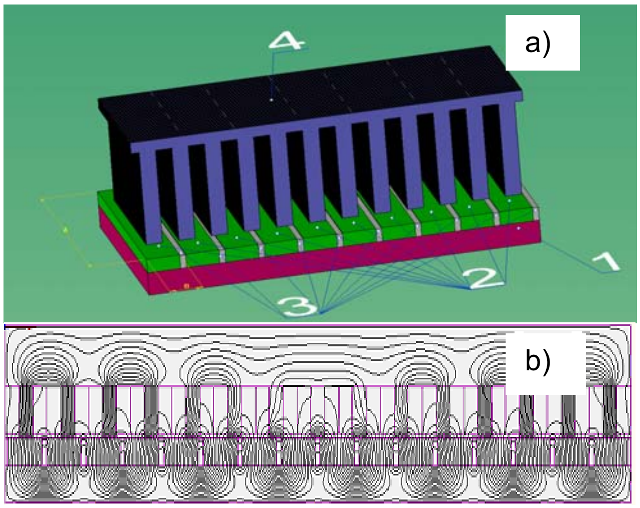

Fig. 2 a)Three-dimensional construction model (without beveling the permanent magnets); 1-magnetic circuit to close the magnetic flux; 2- permanent magnets; 3-non-magnetic separators; 4-pack of ferromagnetic core, b) 3D flux lines view of the original LSDPM.

3D FEM analysis software is used to model and analyze the three-dimensional magnetic field of a linear motor [6].

All the electromagnetic phenomena can be described by Maxwell equations in LSDPM [10,12,14,16,17]. Generally, the effect of displacement current isn't considered, so the air-gap magnetic field is stable in vertical direction. The expression of parallel plane field as follows:

$$(1)\qquad \begin{cases} rot\ \vec{H} = \vec{J} \\ div\ \vec{B} = 0 \\ \vec{B} = \mu_r \mu_0 \vec{H} \end{cases}$$

where $\vec{H}$ is the magnetic field intensity, $\vec{B}$ is the magnetic induction, $\vec{J}$ is current intensity, μ_r is the differential permeability, μ_0 is the permeability of vacuum.

Considering the saturation effect of ferromagnetic material, the above vector equation can be simplified as follow:

$$(2)\qquad \frac{\partial}{\partial x}\left(\frac{1}{\mu_r \mu_0}\frac{\partial A_z}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{1}{\mu_r \mu_0}\frac{\partial A_z}{\partial y}\right) = -\vec{J}_z$$

There is no initial condition in magnetic field of PMLSM, the solution of field is determined by boundary conditions.

(3) $$\begin{cases} S1: A = A_0 \\ S2: \dfrac{1}{\mu_r \mu_0}\dfrac{\partial A}{\partial n} = -H_t \\ \vec{B} = \mu_r \mu_0 \vec{H} \end{cases}$$

where $S1$ is the first boundary condition, $S2$ is the second boundary condition. These boundary conditions are equivalent to the conditional variation problem of energy function.

(4) $$W(A) = \iint_{\Omega}\left(\int_0^B \frac{1}{\mu_r \mu_0} BdB - J_z A\right)dxdy - \\ - \int_{S2}(-H_t)Adl = \min$$

$A=A_0$ where

$$B = \sqrt{\left(\frac{\partial A}{\partial x}\right)^2 + \left(\frac{\partial A}{\partial y}\right)^2}$$

In this case, the three-dimensional formulation of FEM is based on the T-Ω [7] method, which differs from other methods in that it allows finite elements of different order to exist in the same finite element network. In this method, the magnetic field is represented as the sum of two parts: the scalar potential gradient and in the conductors - an additional vector field represented by vector-edge finite elements.

This method saves a considerable amount of RAM since the problem in non-conducting regions can be solved with the scalar potential of the magnetic field. Moreover, the T-Ω method does not address the issues of convergence and instability, as in the use of other formulations. In the three-dimensional formulation, the first Maxwell equation (Ampere law) is strictly given as

(5) $$div\,\vec{B} = 0$$

is satisfied only approximately.

In solving the three-dimensional problem each vector consists of the scalar magnetic potential plus the edge degrees of freedom associated with the flow of current in the solid wires [6]. In deriving the basic equation that is solved here, the second Maxwell equation is

(6) $$rot\,\vec{E} = -\frac{\partial \vec{B}}{\partial t},$$

without including members associated with the movement of the environment.

The following tensor relationships between the vectors of the field are also used

(7) $$\vec{B} = \mu \vec{H};$$

(8) $$\vec{E} = \left(\gamma + \varepsilon \frac{\partial}{\partial t}\right)\vec{J}.$$

In [4], is the total current given by equation

$$\vec{J} = \vec{J}_\gamma + \vec{J}_D = \gamma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t},$$

in which the dielectric constant t is assumed to be independent of time.

From equations (6), (7) and (8) and the first Maxwell equation

(10) $$rot\,\vec{H} = \vec{J},$$

given by

(11) $$\vec{\nabla} \times \left[\left(\sigma + \varepsilon \frac{\partial}{\partial t}\right)^{-1} \vec{\nabla}\vec{H}\right] + \mu \frac{\partial \vec{H}}{\partial t} = 0.$$

Current sources I_K with cross section S_K and boundary circuit LK impose restrictions

(12) $$\iint_{S_k} J_\gamma\, ds = I_K.$$

and

(13) $$\iint_{S_k} \vec{\nabla}\vec{H}\, ds = \oint_{L_K} \vec{H}\, d\vec{l} = I_K.$$

The magnetic field intensity vector is obtained by solving equation (11). Then magnetic induction and current density are obtained from (7) and the first Maxwell equation (10).

For a non-conducting medium, the first Maxwell equation is solved

(14) $$\vec{\nabla} \times \vec{H} = \vec{J}_S,$$

where $\vec{J}_S$ is the current density of an eventual coil $\vec{J}_S = 0$ (outside the coil winding). Then the intensity of the magnetic field $\vec{H}$ can be writen

(15) $$\vec{H} = -\vec{\nabla}V_M + \vec{H}_S,$$

where $\vec{H}_S$ is an arbitrary current source that satisfies the equation

(16) $$\vec{\nabla} \times \vec{H}_S = \vec{J}_S,$$

and the scalar potential of the V_M is such that

(17) $$\vec{\nabla}\vec{B} = \nabla\left[\mu\,(-\vec{\nabla}V_M + \vec{H}_S)\right] = 0.$$

An iterative procedure is used to find a field source to satisfy (17). The scalar potential of the magnetic field V_M is obtained by solving equation (17) and then $\vec{H}$, $\vec{B}$ and $\vec{J}$ are obtained by (15), (7) and (10) respectively.

Fig.3 shows a three-dimensional model of a linear motor for magnetic field analysis with FEM (Finite Element Method) [4,11,12]. The model lacks the motor winding, since, as stated above, the calculation of the power is done in the absence of current in the windings. They are also wound by a copper conductor, which is a non-magnetic material and therefore does not affect the magnetic field distribution in this case.

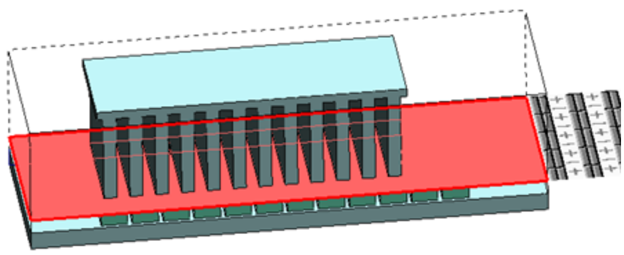

Fig. 3 Three-dimensional FEM model for calculating the detent force.

The model is parameterized by the position (coordinate x) of the ferromagnetic core with respect to the permanent magnets to simulate motion. Set values for its displacement in 0.5 mm increments within one 15 mm pole, ie. one period of resistance change.

In connection with the simulation, movement of the moving part is solved by the problem of magnetic field analysis under the following boundary conditions:

(a) the movable and fixed parts are surrounded by two different "Air boxes" [4] that touch exactly on the surface lying in the middle of the air gap (selected in red in Fig. 3);

(b) Odd periodic boundary conditions [4] shall be a fixed to the surfaces of the two "Air boxes" with which they touch.

To reduce the time required to solve a 3D problem, the linear properties of the magnetic materials are set. This is due to the fact that the holding force does not depend on the nonlinearity of the magnetic properties, but mainly on the geometry of the magnetic system.

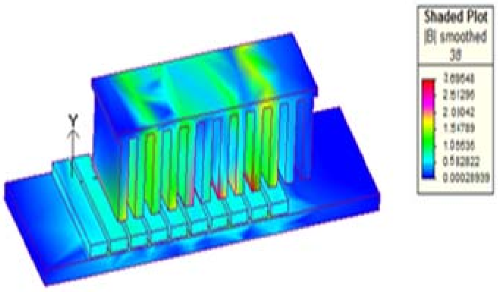

Fig. 4 Magnetic induction distribution for x=15 mm

The magnetic induction distribution obtained for a particular displacement of the movable relative to the fixed part is shown in Fig. 4.

For linear synchronous motors, permanent magnets are cut at a certain angle to reduce the magnitude of the detent force. For the purpose of the linear motor design studies, the permanent magnets are beveled as shown in Fig. 5.

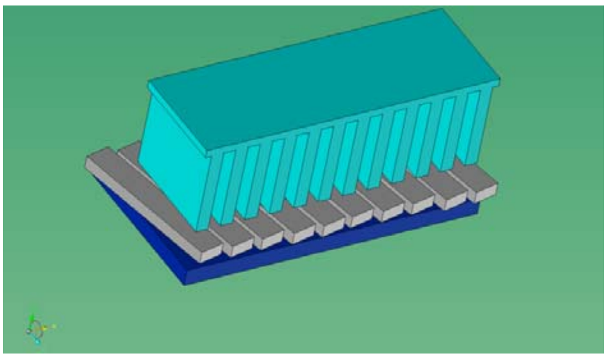

Fig. 5 Bevelling of permanent magnets.

The optimal angle is determined using the FEM. The angle of inclination is changed with a certain step and its value is sought at which, based on the results of the analysis of the magnetic field, a component of the force on the movable part on the Ox axis in the absence of current in the motor winding is minimal. It starts from $\alpha = 9{,}44^0$ the fact that it corresponds to a bevel of permanent magnets in a single channel division.

Since the problem is three-dimensional, a three-dimensional numerical model is also used to analyze the stationary magnetic field of the engine in the area shown in Fig. 5.

According to the results of the implementation of the program, the dependence of the detant force on the position of the movable part is constructed within one pole division $F_{det}=f(t)$, shown in Fig. 6a for 0^0 - ie no bevel magnets.

From this figure, it is found that the detent force is 30 N. This necessitates the need to take special measures to reduce it. Here, the reduction of the detent force will be investigated by tilting the permanent magnets, ie placing them at a certain angle in the direction of motion.

It is known from the classical theory of AC electric machines that in order to reduce the magnitudes of the amplitudes of some higher harmonics, the stator (or rotor) channels are truncated into a single channel division. This is also widely used in rotary synchronous motors to reduce the amount of cogging moment.

From the researches done, it is found that the greatest decrease of the detent force is obtained by bevelling the permanent magnets at an angle $\alpha = 30^0$, Fig. 6b.

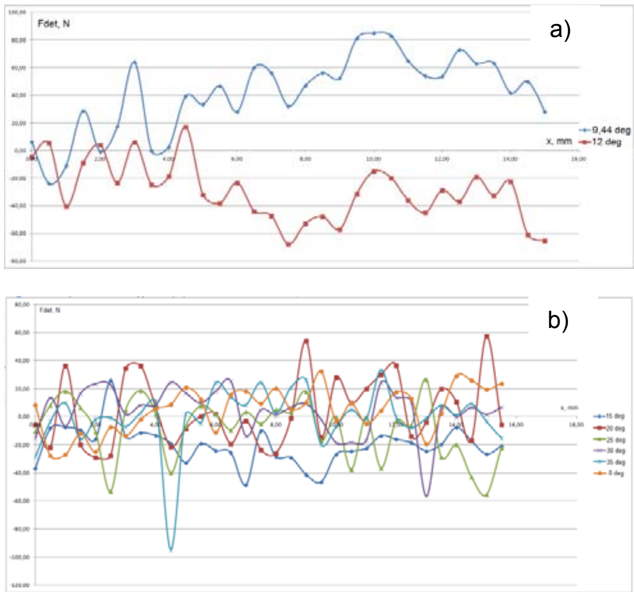

Fig. 6 Dependence of the bevel force on the position of the movable part at different angles of beveling a) α=30^0 of the permanent magnets, and b) without beveling.

If, however, the motive force is calculated when angle $\alpha = 30^0$ of the magnets are skewed, a significant decrease in motive power is obtained compared to the absence of bevel shown in Fig. 7. The same is confirmed by studies published in the literature.

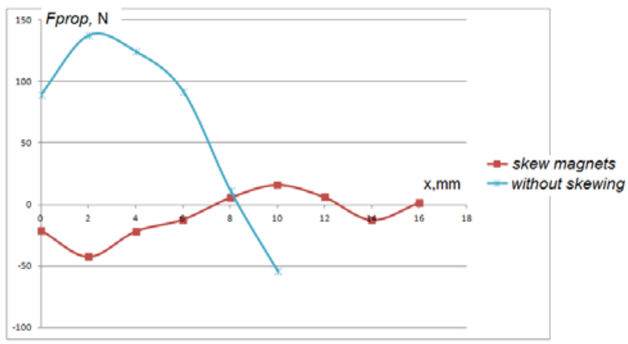

Fig. 7 Comparison between the motive forces

The analysis of the magnetic field of the motor in the three-dimensional case also makes it possible to calculate the force of attraction of the ferromagnetic core to the permanent magnets, whose knowledge enables the correct dimensioning of the linear guide.

It is equal to the component of the force on the movable part on the axis Oy, calculated with FEM, Figure 8.

Fig. 8 Dependence of the constituent of the force on the movable part on the axis Oy from the position of the movable part with respect to the permanent magnets at an inclination angle $\alpha=30^0$.

In addition, by tilting the permanent magnets at a certain angle, the electromagnetic force component along the axis Oz acting on the movable part is shown, which is shown in Fig. 9. It is also calculated on the basis of the results of the magnetic field analysis with FEM.

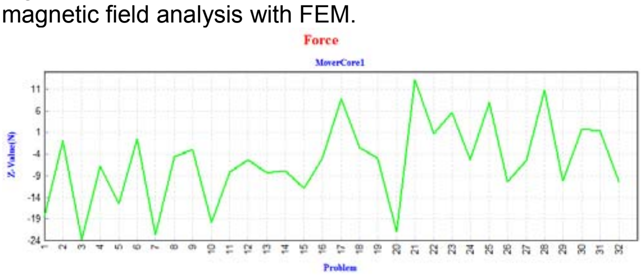

Fig. 9 Component of the force on the movable part on the Oz axis at $\alpha=30^0$.

This component additionally loads the linear guide perpendicular to the direction in which the moving part of the LSDM moves and impairs its dynamics. It should be taken into account by designers and designers ofthis type of linear motor whenchoosing a linear guide.

Experimental research

In order to verify the results of the calculation of the Fdet engine detent force with the FEM, an experimental study of the engine prototype should be carried out in order to measure this force. As noted earlier, this force acts even when no current I = 0A flows through its windings.

Therefore, it can be easily measured and will be equal to the applied force, under whose action the movable part moves in the desired direction without coil being powered by the driver. The kinematic scheme of Fig. 10 is used for its measurement, and the loading of the movable part is made by means of calibrated weights.

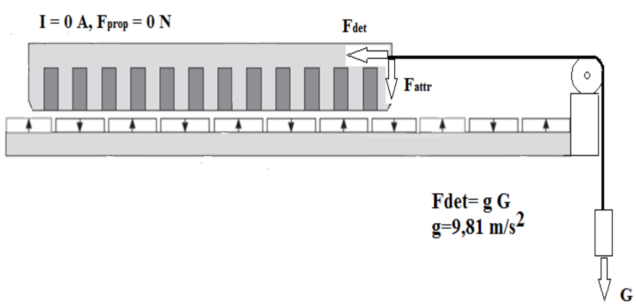

Fig. 10 Kinematic scheme of the experimental setup for measuring the detent force

The measurement results are summarized in Table 2.

Table 2. Detention force values from FEM calculation and experiment

Size	Calculation with FEM	Experiment	Relative error, εм%
Maximum detent force value, N	30	26,2	-14,5

This table compares the results of the FEM calculations with a good match experiment.

Conclusions

The research done in this work shows that the positioning of permanent magnets at a certain angle (bevel) results in a significant reduction of the detent force on the movable part in linear synchronous permanent magnet motors mounted on the surface of the magnetic circuit to close the magnetic flux. At the design stage of a linear motor, the calculation of this force can be done with the FEM based on the results of the stationary magnetic field analysis. The resisting force is equal to the component of the Ox axis force acting on the movable part in the absence of excitation current through the motor coil. The analysis of the field in the three-dimensional case also makes it possible to calculate the constituent of this force, along the axis Oy, which represents the force of the magnetic conduction of the moving part to the permanent magnets. This knowledge is also very important in designing the engine for proper sizing of the linear guide.

However, the reduction in detent force due to the constriction of the permanent magnets is accompanied by the negative effects of reducing the motor force and the appearance of force acting perpendicular to the direction of movement along the Oz axis.

For these reasons, well analized in the simulations in the present work, the placement of permanent magnets at a certain angle with respect to the direction of motion of the moving part was not accepted as a way of reducing the detent force in the design and construction of the prototype of the linear servo motor under study. The application of this method must be accompanied by a mandatory 3D simulation of the engine.

The models of the linear FEM for the linear synchronous motor developed in this publication and the results of the research done are important for designers and constructors of linear synchronous permanent magnet motors.

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