A Novel Double Salient Permanent Magnet Linear Motor

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ABSTRACT

The market for linear motors and drives is expected to more than double to over $ 200 milion by 2002 because these products afford lots of benefits. In these circumstances it may be interesting a novel high performance linear motor structure. In this paper a novel double salient permanent magnet linear motor structure is proposed and analysed. The results obtained via computer simulation stand by to sustain the pertinence of the proposed motor design.

1. INTRODUCTION

The main advantage of any linear motor is that it totally eliminates the need, cost and limitations of mechanical rotation-to-translation mechanisms such as racks and pinions or belts and pulley, sources of elasticity and backlash. This way the complexity of the mechanical system is drastically reduced.

The first electromagnetic linear motor was put together as long ago as 1845 (the Wheatstone's linear motor). Since then several linear motor types were widely utilised efficiently in divers applications: permanent magnet synchronous linear motors, brushless D.C. linear servomotors, moving magnet and moving coil linear motors, etc. Although all these linear motors are competent, novel linear motor structures, such as that to be presented in this paper, can be marketable.

The starting-point of designing the innovative linear motor structure was the well-known hybrid linear stepper motor shown in Fig. 1. [1, 2]. In fact it is a variable reluctance, permanent magnet excited synchronous motor, having a movable armature (the mover or forcer) suspended over a fixed stator (the platen). The platen is an equidistant toothed bar of any length fabricated from high permeability cold-rolled steel. The mover consists of two electromagnets having command coils and a strong rare earth permanent magnet between them, which serves as a bias source. Each electromagnet has two poles, and all poles, toothed to concentrate the magnetic flux, have the same number of teeth. The toothed structures in both armatures have the same fine teeth pitch. The four poles are spaced in quadrature, so that only one pole at a time can be aligned with the platen teeth.

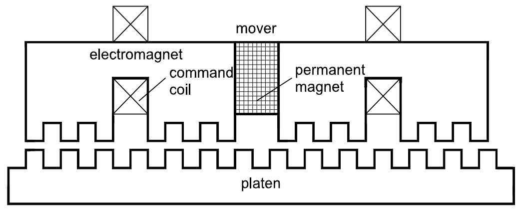

Figure 1. The hybrid linear stepper motor

The hybrid linear stepper motor is operating under the combined principles of variable reluctance and of permanent magnet motors. When current is established in a command coil, the resulting magnetic flux tends to reinforce the flux of the permanent in one pole of that electromagnet and to cancel it in the other. By selectively applying current pulses to the two command coils, it is possible to concentrate flux in any of the poles. The pole receiving the highest flux concentration will attempt to align its teeth with the platen teeth by generating a tangential force, in a manner as to minimise the air-gap magnetic energy. Four steps result in motion of one tooth interval.

The above-presented motor type has some disadvantages. As the electromagnets are not definitely independent, the magnetic flux produced by the command coils flows through the permanent magnet, existing the peril of its demagnetisation. In any position one of the poles is generating a significant breaking force, diminishing the total tangential force produced by the motor and reducing its efficiency [2]. Beside these the magnetic flux passing between the mover and the platen gives rise to a very strong normal force of attraction between the two armatures. This attractive force, produced of all the poles, is over 10 times the peak holding force of the motor, requiring sophisticated bearing systems to maintain the precise air-gap between the mover and platen. The greatest attractive force is generated of the same pole that produced the breaking tangential force (the pole those teeth were aligned with the platen teeth before starting the current step).

These disadvantages could be eliminated by reducing significantly the magnetic flux passing through the passive poles (the two poles of that electromagnet of which command coil is not energised). A possible solution to this problem it could be the proposed innovative double salient permanent magnet linear motor.

The characteristics of the novel linear motors were computed via a simplified circuit-field mathematical model. They were compared with those obtained for an equivalent hybrid linear stepper motor.

The obtained results were checked on by a numeric magnetic field computation procedure via MagNet 5.2, partially avoiding the lack of test results.

All the obtained results sustain the relevance of the next proposed novel linear motor structure.

2. THE MOTOR STRUCTURE

The double salient permanent magnet linear motor to be presented has essentially the same construction as a classical switched reluctance machine, with the single difference that it has high-energy magnets placed in the mover.

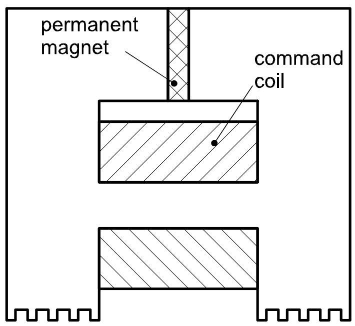

Figure 2. The mover module of the double salient permanent magnet linear motor

The mover of this motor is built up of several independent modules like that presented in Fig. 2., existing the possibility to use different number of modules. Each mover module has two pole pieces, a permanent magnet excitation source and a command coil. The command coil is placed on a core branch in parallel to the permanent magnet. The two poles of the module are spaced in a way as if the teeth of one pole are aligned with the teeth of the platen, than the teeth of the other pole are also aligned with the platen's teeth.

The design procedure of the motor is based on several relationships obtained from the simplified analytical motor model [3] and on some experience resulted values for the most important motor dimension ratio [4]. The sizes of the two most sensitive components of the module (the permanent magnet and the command coil iron core) were computed very carefully. The importance of the permanent magnet selection must be emphasised, the most expensive and sensitive assembly of the whole motor. It was taken into account the maximum imposed temperature rise in the mover and the cost to performance ratio. The above mentioned core branch has the role to close the magnetic flux path if the command coil is not energised in a way as to reduce to minimum the magnetic flux through the air-gap. If this piece is correctly designed, there is no peril of demagnetisation for the permanent magnet. The command coil can be used as a magnetisation device, too.

As it is well known, with regard to application, a distinction can be made between two linear motor embodiments: the precision linear motor and the industrial linear motor. Precision linear motors are intended primarily for high-precision applications. For industrial linear motors on the other hand the following chief objectives can be named: simple system integration, suitability for severe industrial environments, simple maintenance, long life, etc. Using the previously presented modules, motors of both categories can be assembled. The resolution of the motor is determined by the distance between two neighbour modules. By increasing the number of the modules placed in the same position relatively to the platen teeth the produced tangential force can be multiplied. This way the linear motor assembly can be easily designed and constructed specially for every specific application, allowing optimal adaptation to the particular application and being capable of satisfying extreme requirements, too.

In Fig. 3. a simple motor construction using the above presented mover modules is presented. The platen is the same as that of the reference hybrid linear stepper motor, shown in

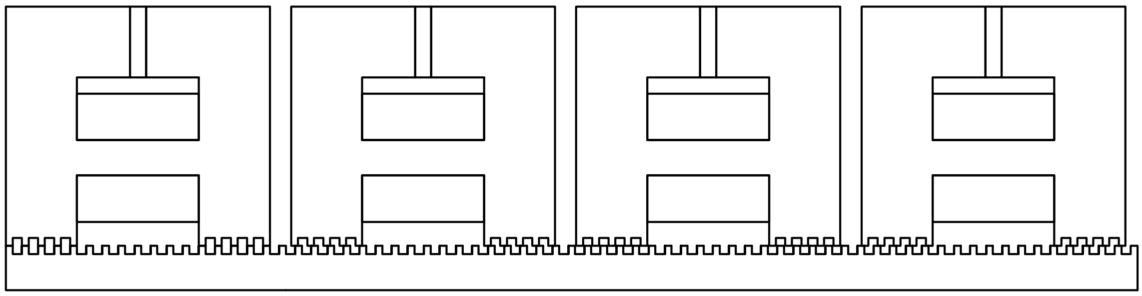

Figure 3. A possible configuration of the double salient permanent magnet linear motor

Fig. 1. The mover is assembled of four modules, displaced relatively by the 2/3 of the teeth pitch.

All the developed force is applied directly to the load and the performance achieved is independent of the length of the platen. The total magnet volume it was taken equal to that of the reference motor, to be able to make a correct comparison of the two motor types.

In Table I. the most significant motor characteristics are presented.

Nr. of poles	8
Nr. of teeth per pole	5
Tooth width	0.84 mm
Slot width	1.16 mm
Tooth pitch	2 mm
Pole area	733 mm^2
Nr. of command coils	4
Nr. of coil turns	200
Motor width	83 mm
Air-gap	0.1 mm
Nr. of permanent magnets	4
Residual flux density	0.9 T
Coercive force	650 KA/m

Table I. The main motor characteristics

An air bearing system maintains the required air-gap between the two armatures during the mover's travel along the platen, providing straight, stiff and cog-free motion at low resolutions, assuring virtually unlimited life for the motor.

As the command coils require only monopolar current pulses, the control circuits are simple. The motor can be driven and controlled in both open-loop and closed-loop configuration.

The motors under discussion have several benefits: low cost, ruggedness, simplicity in construction, high reliability, no maintenance, wide acceptance and they work in just about any environment. In the same time these motors have the following disadvantages: resonance effects and relatively long settling times, liability to undetected position loss in open-loop control mode, current consummation regardless of load conditions. Many of these drawbacks can be overcome by a closed-loop control scheme.

A complete list of the possible applications for this new designed motor can hardly be stated. Nevertheless there are of course both hard technical application limits and areas where other technologies are better suited, depending on load conditions and system environment. Some imaginable applications include computer peripherals, machine tools, laboratory automation systems, component placement machines, positioning tables, factory automation applications, etc.

3. COMPUTER SIMULATION

All the main motor characteristics were computed by an analytical coupled circuit-field model, presented in several previous papers [1 ,2]. The model takes into account the complex toothed configuration, the magnetic saturation of iron core parts and the permanent magnet operating point changes due to air-gap variable reluctance and control amperturns, too. It is based on an equivalent magnetic circuit of the motor. The analytical results can be helpful in verifying the motor's design and in elaborating an optimal control strategy.

All the computations were done supposing that the initial mover position is that one given in Fig. 3., and the mover's displacement is to the right, *x* co-ordinate increasing.

There are numerous motor performance characteristics that warrant discussion. In order to be able to compare the novel double salient permanent magnet linear motor with the hybrid linear stepper motor the mathematical predictions are focused on the two tangential force characteristics of the above mentioned motors (presented in Figs. 4 and 5), which traits with the greatest practical

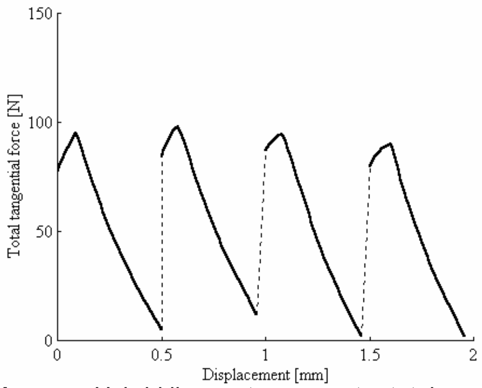

Figure 4. Hybrid linear stepper motor total tangential force function of displacement

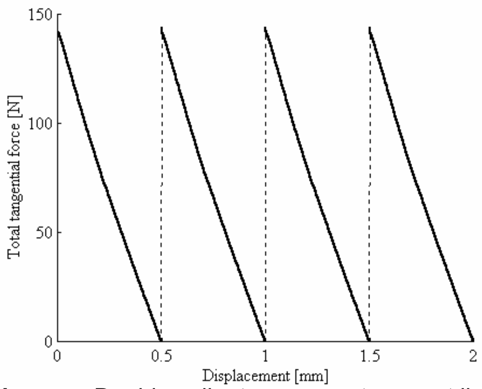

Figure 5. Double salient permanent magnet linear motor total tangential force function of displacement

significance. These relate to the motors energised but stationary. They show us how the total tangential force varies with mover position. It was assumed that there were no frictional or other static loads on the motor. These characteristics were plotted for a displacement equal to four full steps (2 mm).

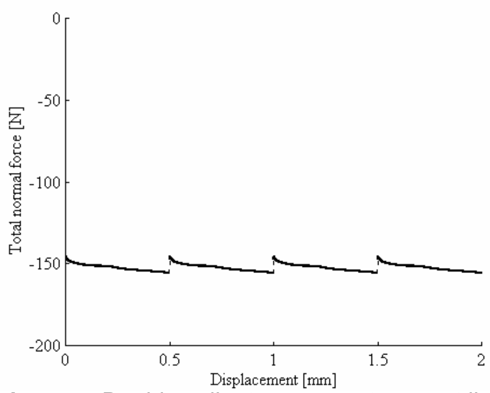

Figure 6. Double salient permanent magnet linear motor total normal force function of displacement

In both cases as the mover is displaced away from its stable position, the total tangential force rapidly increases to its maximum value, the so-called holding force, which represents the largest static load that can be applied to the motor without causing continuous movement. After reaching its peak value the total tangential force is decreasing until near nil after fulfilling a movement of one step. The characteristics were continued to be plotted for the next sequence of energising the command coils.

The total normal force versus displacement of the double salient permanent magnet linear motor is presented in Fig. 6.

The obtained results were checked on by a finite element method (FEM) based numeric magnetic field computation procedure (usising the MagNet 5.2 package).

The computations were made for a single mover module (that shown in Fig. 2). The equipotential lines presented in Figs. 7 and 8 were plotted for zero, respectively for the maximum value of the command coil current (2 A).

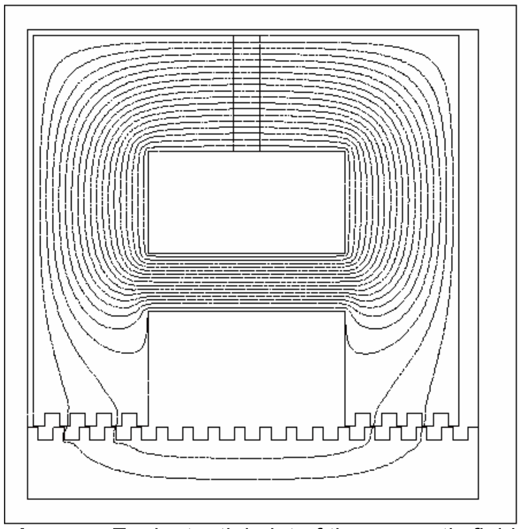

Figure 7. Equipotential plot of the magnetic field for no-load condition

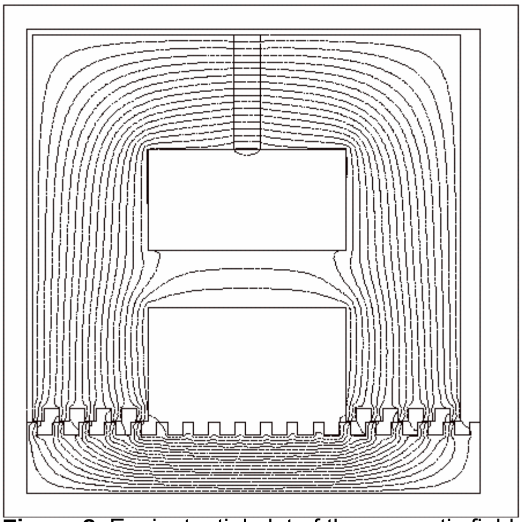

Figure 8. Equipotential plot of the magnetic field for maximum command current

4. CONCLUSIONS

Although the presented characteristics are not a great deal of use on there own, they do help explain some effects that are observable.

As it can be clearly seen, the peak value of the total tangential force of the double salient permanent magnet linear motor (144 N) is much more greater that of the hybrid linear stepper motor (98 N). Of course the computed medium values of these forces (51.8 N, respectively 68.4 N) show the higher force capability of the new designed motor.

For the hybrid linear stepper motor the maximum values of the total tangential forces are not equal for all the four poles due to magnetic asymmetry between inner and outer poles.

The higher thrust capacity was obtained using the same amount of permanent magnet (detached in four pieces) for the novel motor construction and the command current pulses were 2.66 times greater. The higher amperturns were needed to obstruct magnetic flux inside the command coil. This way nearly all the flux generated by the permanent magnet was utilised for the force production. Since the characteristics presented in Fig. 5 are nearly linear, it simplifies the optimal control strategy to be adopted.

As far as the total normal force of the double salient permanent magnet linear motor is concerned, Fig. 6, it can clearly be seen that these attractive forces are much smaller than those observed for other flat type linear motors. Nevertheless the normal force ripple (only about 10 N) is quit small, simplifying the control of the air-bearing system.

The equipotential plots for the magnetic field in the motor show very clearly the usefulness of the core branch placed under the magnet. When the command current coil is un-energised, the flux generated by the permanent magnet flows mainly through this iron core, minimising the flux passing through the air-gap and diminishing the needless forces in this case. On the other hand, when the command current is set at its maximum value, then nearly the entire flux of the magnet is concentrated through the air-gap area, giving rise to a significant force production.

In order to compare the results obtained via the two utilised models, the magnetic flux in the middle of the command coil iron core was computed. Using the above-mentioned analytical model $1.008\ 10^{-3}$ Wb was obtained. The same magnetic flux computed utilising the MagNet 5.2 package was of $1.12\ 10^{-3}$ Wb. It means that the field computations via the two methods give nearly the same results.

The forces computed by the FEM-based method are greater that those computed by the analytical method (163 N for the tangential force and 185 N for the normal force). The differences probably are caused by the distinct force computation methodology utilised.

In all the cases where high thrust and high precision are required, the use of these new motor types ought to be considered. Their unique properties militate in their favour where linear motions have to be executed not only gently and exactly, but at the same time dynamically and freely programmable, too. In view of all this one is justified in speaking of and innovation drive, that may be set in motion in a variety of fields.

It is worth mentioning that the authors had been concentrated on performance modelling and analysis of the motor's behaviour, and a full electromagnetic optimisation using numerical field computations has not yet been made.

In the future also an optimal control strategy must be elaborated to reduce the significant tangential force ripple of the motor and to improve its performances.

5. REFERENCES

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