3D FINITE ELEMENT COMPUTATION OF A LINEAR TRANSVERSE FLUX ACTUATOR

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INTRODUCTION

The principle of operation of a linear permanent magnet transverse flux motor has been described in a previous paper [2]. This actuator is intended to operate in a computer peripheral device which requires a fast and accurate positioning, while the dimensions are strictly limited. Transverse flux machines can achieve such a high force/volume ratio and are therefore suited for this application.
As explained in detail below, the particular configuration with two motors facing each other described in [2] not only makes optimal use of the available volume, but allows also an advantageous combination of the force profiles of the two motors. Due to the complexity of the flux path in the airgaps, a parameterized 3D finite element model has been set up to allow an accurate computation of the force acting on the mover. Particular attention has been paid to end effects. The principle of operation of the machine has been established on basis of these results and the performances of the actuator have been compared with the specifications.The influence of the number of mover blocks has been studied with a view to the geometrical optimization of the mover.

SPECIFICATIONS

The following parameters are specified:

- the maximum length, height and width of the rectangular box enclosing the whole actuator.
- the travel distance of the mover, which corresponds to 75 % of the length of the machine.
- the minimum acceleration of the mover. In addition, the system must be designed in such a way that, at any position, it is possible to apply to the mover a force of any value in the range $[-F_{max}, F_{max}]$, where F_{max} is the given maximum force.

DESCRIPTION OF THE ACTUATOR

The actuator described in this paper consists of the combination of two independent motors facing each other (Fig. 1). Each stator can be seen as a long C-core with toothed lower and upper branches. A coil is wound around the vertical core. The stators of the two machines are shifted in space by a quarter of a pole pitch, so that the reluctance forces in the X-direction cancel each other out.

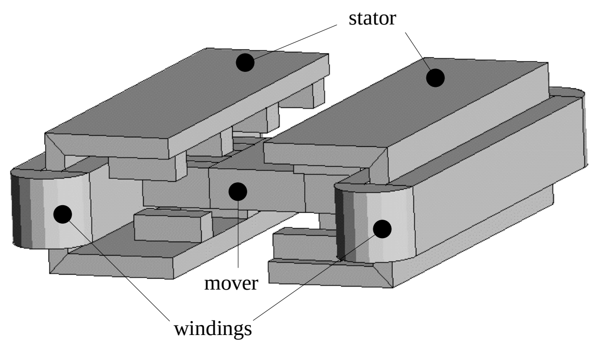

Figure 1: Geometry of the overall transverse flux actuator.

The movers of both actuators are made of alternate blocks of iron and high energy magnets, magnetized in the direction of the movement, i.e. the X-axis. They are separated by a nonmagnetic block in order to avoid flux passing from one machine to the other (Fig. 2).

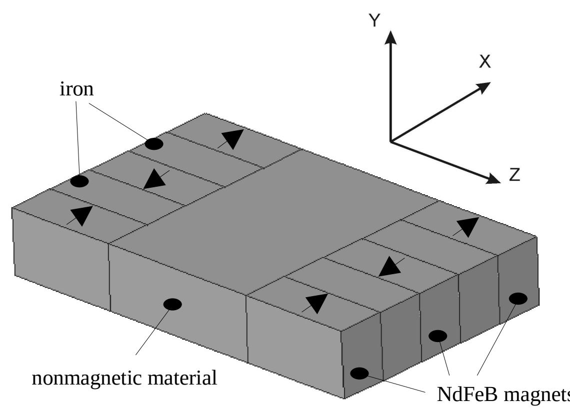

Figure 2: Co-ordinate axes with respect to the mover.

The magnet and iron blocks forming the mover have the same length as the stator teeth in the X and Z directions. The pole pitch is equal to four times the block length. The position of the mover is measured with respect to a reference position for which the first block of the mover is aligned with a stator tooth (Fig. 3).
The dimensions of the whole actuator are chosen so as to remain within the admissible limits.

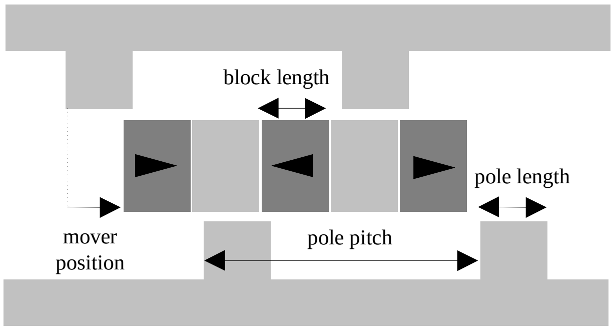

Figure 3: Characteristic dimensions of the actuator.

FINITE ELEMENT MODEL

Under certain conditions, a magnetic equivalent circuit can describe the flux distribution in a permanent magnet linear machine, and accurately determine the developed force at a low computational cost [1]. In transverse flux machines however, the intricate geometry renders such a simplified approach troublesome [3][5]. A more versatile method, such as the finite element method, is preferable here. In order to take 3D effects occurring in the airgap and around the mover into account, a 3D model is set up.

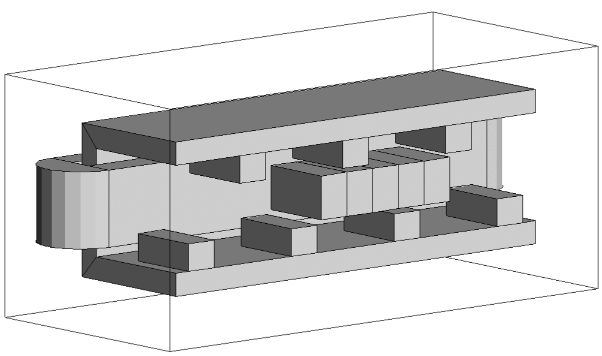

Figure 4: 3D finite element model of the actuator.

Since the movers are mechanically connected but magnetically independent, it is sufficient to model one of the two motors. The finite element model thus represents only one machine (Fig. 4), and the computed force profiles shown further on account for one motor as well, unless otherwise specified. If the dimensions and thus the mass of the mover are fixed, the minimum force F_{min} that has to be applied to reach the specified acceleration can be determined. This value has been taken as reference and all values of the force given in this paper are expressed as relative values.

PRINCIPLE OF OPERATION

A first set of calculations is carried out with a 5-block mover made of three permanent magnets blocks magnetised in alternate directions and separated by two iron blocks (Fig. 3). The problem is solved at different positions within one pole pitch, the other configurations being deduced by periodicity. End effects are considered later.

The components of the force acting on the mover when the coil current is zero, i.e. the components of the reluctance force, are shown on figure 5.

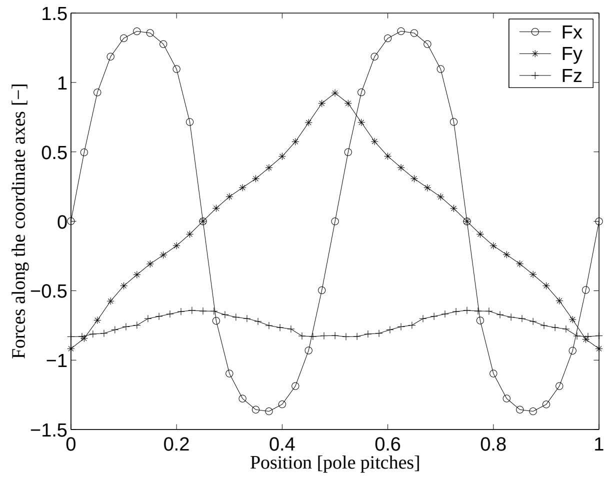

Figure 5: Reluctance force along the X, Y and Z axes as a function of the mover position.

One sees that the reluctance force in the direction of motion, F_x, is periodic with a period equal to half a pole pitch. Since the stators of both machines are shifted by one half of this period, i.e. a quarter of a pole pitch, the total reluctance force are approximately zero. The reluctance force in the vertical direction, F_y, has a triangular shape, with a period equal to one pole pitch. The force in the transversal direction, F_z, varies slightly around a constant value. It cancels out also with the transversal force developed by the second machine and is not further discussed in this paper.
With a current density ranging from –10 A/mm^2 to 10 A/mm^2, the results of figures 6-7 are obtained. The period of F_x is now equal to one pole pitch (Fig. 6).

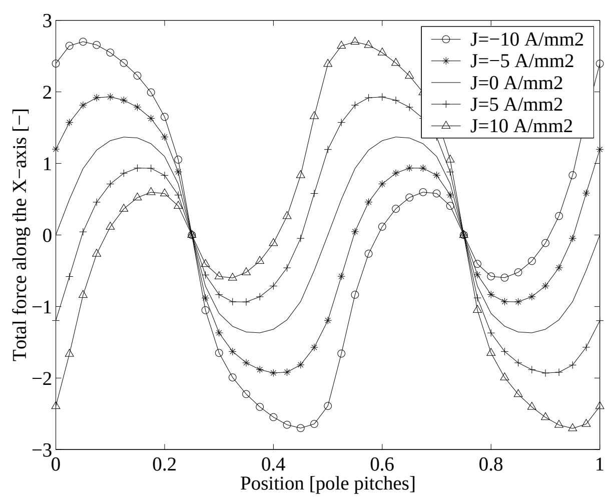

Figure 6: Total force in the X-direction when the current density ranges from –10 A/mm^2 to 10 A/mm^2.

It can be split up into the quasi-sinusoidal reluctance force F_{x_rel} caused by the permanent magnets, and a triangular shaped net force F_{x_net}, proportional to the coil current (Fig. 7).

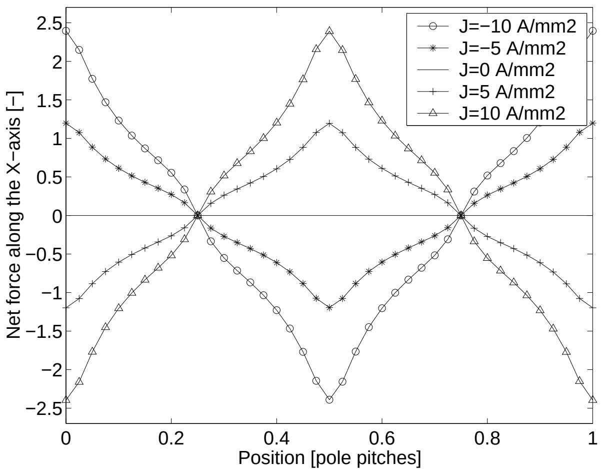

Figure 7: Net force in the *X*-direction when the current density ranges from –10 A/mm^2 to 10 A/mm^2.

Since F_{x_rel} is nearly zero for the complete system, the total force in the *X*-direction is the sum of the net forces acting on the left and the right part of the mover, of which the coils are fed independently. Thanks to the shift between the two actuators, a minimum of F_{x_rel} for one actuator corresponds to a maximum for the other. Ideally, by appropriately reversing the coil currents, a constant force of given amplitude could thus be applied on the mover, regardless of its position (Fig. 8).

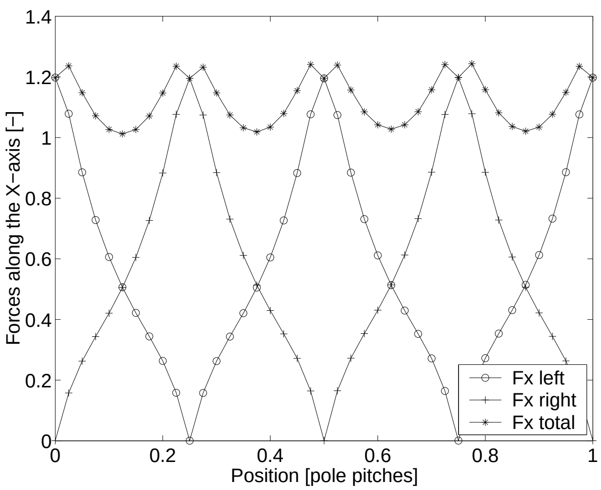

Figure 8: Net forces acting on the left and right parts of the mover, and total net force; J=±5 A/mm^2.

In practice, the obtained force is not position independent. If the coil current density equals 5 A/mm^2, the minimum, maximum and mean values of the force are reported in table 1. The force ripple, defined by equation (1), is indicated as well.

$$FR = \sqrt{\frac{1}{L}\int_0^L \left(F(x) - Fmean\right)^2\, dx} \qquad (1)$$

Table 1: Minimum, maximum, mean and ripple of the forces in the *X*-direction; J=5 A/mm^2.

	Reluctance force	Net force	Total force
Min	-0.22	1.01	0.98
Max	0.22	1.24	1.46
Mean	0.0	1.12	1.12
Ripple	0.13	0.08	0.15

It follows from this table that the force ripple is mainly due to the imperfect cancelling out of reluctance forces. The minimum force meeting the requirements is already achieved with a coil current density equal to 5 A/mm^2, although the duty cycle would allow current densities up to 10 A/mm^2.

The magnetic flux flowing through the airgap is represented on figure 9 for three values of the current density. The flux is expressed as relative value, the reference being the maximum value of the flux when the coil current density is zero.

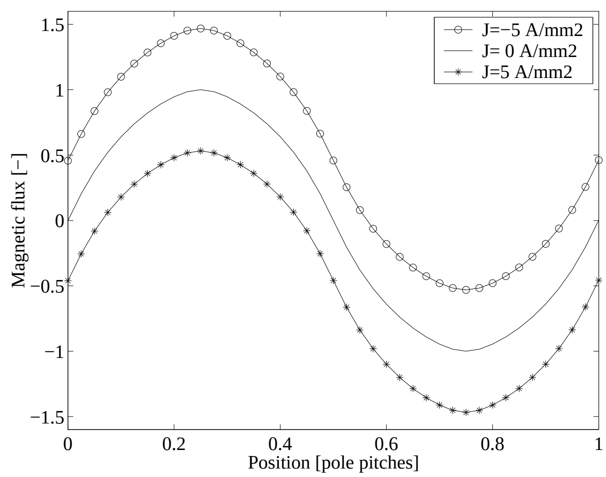

Figure 9: Magnetic flux flowing through the airgap as a function of the mover position.

The shape of the flux profile is sinusoidal with respect to the position. However, the difference between two values computed for different current densities is constant over the whole range, and proportional to the applied current. Non-linearities thus do not play an important role, at least if the absolute value of the coil current density does not exceed 10 A/mm^2.

END EFFECTS

The motor described in this paper must fit in a volume of strictly limited dimensions, and must operate a specific device over 75 % of its total length. This limits the maximum length of the mover to 25 % of the motor length. A strong modification of the force profile at the ends of the actuator could complicate the control system, or even prevent an efficient operation at the minimum respectively maximum mover position. In that case, the total length of the motor should be increased to compensate the reduction of the effective range of the mover. This would be a severe drawback for the present application anyway. Consequently, attention has been paid to the behaviour of the machine when the mover approaches the ends of the stator. The forces at the end and in the middle of the stator are compared with each other. The same relative positions of the mover and stator poles are chosen.

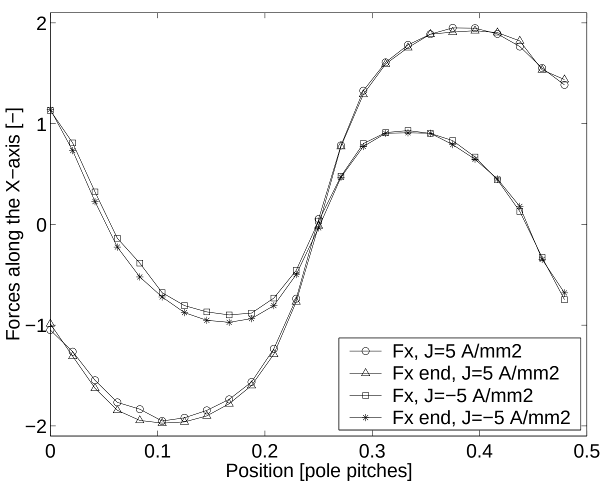

Figure 10: Total force in the *X*-direction, depending on whether the mover is in the middle or at the end of the stator.

Obviously, the force profile is similar on the whole range of the mover (Fig. 10) and it can be stated that the end effects are negligible.

DESIGN OF THE MOVER

In the previous section, the characteristics of the actuator have been investigated with a mover arbitrarily designed of five blocks, three magnet blocks and two iron blocks. However, the number of blocks is also a parameter that must be chosen so as to maximize the developed force. Therefore, its influence on the force profile has been analysed. Four configurations, corresponding to a mover made up of 3, 5, 7 and 9 blocks (respectively 2, 3, 4 and 5 magnets) have been studied. The total length of the mover is kept constant, so that the block length L_b and the volume of permanent magnet material decrease as the number of blocks increases. The stator teeth length and the pole pitch, equal to L_b and $4\,L_b$, are modified accordingly.

Due to the size of the actuator, a number of blocks greater than seven leads to unrealistically thin magnets. However, in order to broaden the range of results, and since the present analysis can be applied to machines of higher dimensions for which this limitation is meaningless, the configuration with 9 blocks has been considered as well.

As shown on figures 11-12, the reluctance forces in the direction of motion have the same profile, whatever the number of magnets, and the net forces are triangularly shaped.

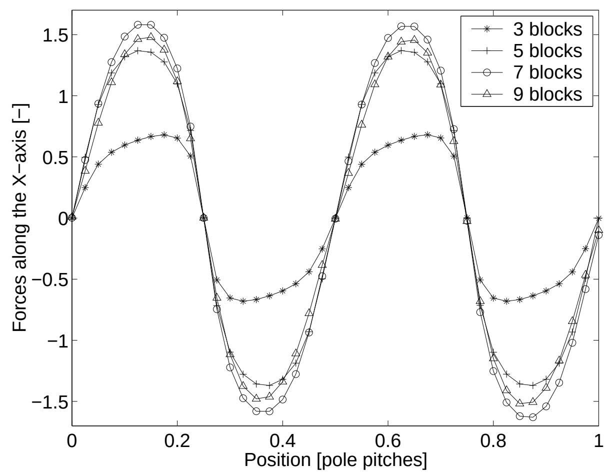

Figure 11: Reluctance force in the *X*-direction as a function of the number of mover blocks.

When the coil current density is set to a given value, the total net force increases significantly with the number of blocks, although the volume of permanent magnet material decreases (Table 2).

Table 2 : Maximum net force as a function of the number of mover blocks; J=5 A/mm^2.

Nb blocks	Net force [-]
3	0.66
5	1.19
7	1.55
9	1.77

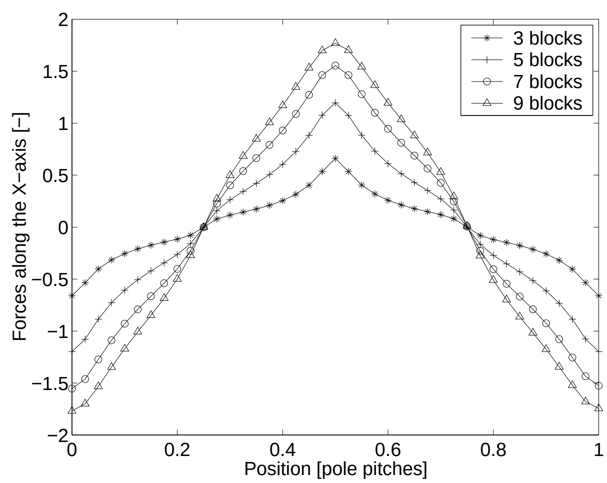

Figure 12: Net force in the *X*-direction as a function of the number of mover blocks.

The vertical force, on the other hand, has a completely different behaviour, depending on whether the number of magnet blocks, n_{PM}, is even or odd. If n_{PM} is odd, F_y is periodic, triangular shaped and independent of the coil current. If it is even, F_y is more like a sinusoid, its maximum amplitude is higher and depends on the coil current.

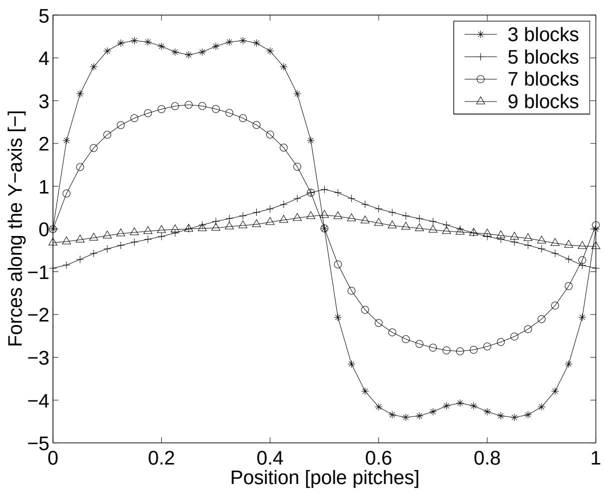

Figure 13: Total force in the *Y*-direction as a function of the number of mover blocks; J=0 A/mm^2.

A mover designed of a higher number of blocks leads to a bigger force in the *X*-direction and seems to be a better choice. However, as mentioned above, this number must be limited to seven in order to avoid unrealistic values of the magnet thickness. On the other hand, the behaviour of the force in the *Y*-direction is strongly dependent on the parity of the number of magnets. If n_{PM} is even, F_y can reach much higher values than in the odd case. Depending on whether this effect must be practically taken into consideration or not, the choice of the optimal number of blocks will be five or seven.

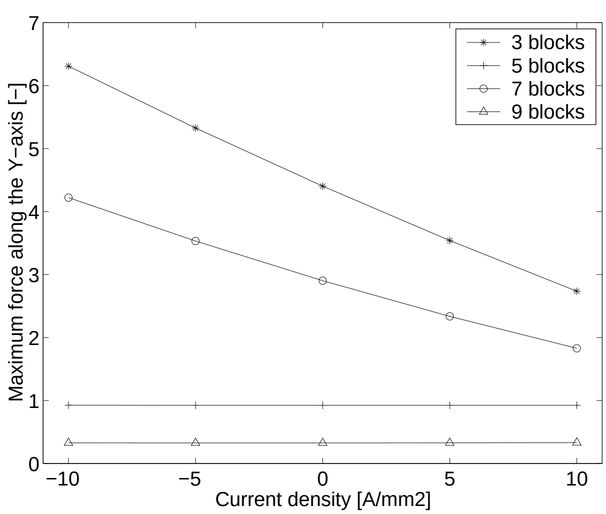

Figure 14: Dependence of the maximum vertical force with the coil current, as a function of the number of blocks.

CONCLUSIONS

A parameterized 3D finite element model of a linear transverse flux actuator has been presented. The profile of the force components along the co-ordinate axes has been computed as a function of the coil current and the mover position, with special attention to the end effects. The operation principle of the actuator has been presented on basis of the obtained results. It has been shown that the proposed motor, whose dimensions remain within the admissible range, can achieve the required acceleration and thus meets the specifications. The results of the 3D FE analysis are used to build a dynamic model of the actuator. This approach, which has not been described in this paper, allows a dynamic analysis of the behaviour of the machine depending on its particular control system.

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