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3D Finite Element Modelling of a Permanent Magnet Linear Actuator

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Abstract: The magnetostatic field and electromagnetic force of a linear actuator with a fixed permanent magnet and soft magnetic mover was studied using the 3D finite element method. The actuator construction is such that its field can be modelled adequately only using 3D analysis. Results were obtained for the magnetic flux density distribution and the electromagnetic force for different positions of the mover for two values of the coil magnetomotive force and two types of permanent magnets.

Keywords: Linear actuators, Permanent magnets, 3D FEM, Electromagnetic force.

1 Introduction

The trend for continuing decrease of power consumption and dimensions of modern electric drives, combined with establishing new generation permanent magnet materials are a prerequisite for the growing interest in permanent magnet systems of different constructions [1-3] and for the possibility to replace the traditional neutral electromagnetic systems employed as actuators.

In the present paper, a construction of a permanent magnet linear actuator is studied and its magnetic field and electromagnetic force are analyzed using the three-dimensional finite element method.

2 Actuator Construction

The principal construction of the studied permanent magnet linear actuator is shown in Fig. 1.

The main elements of the actuator are: permanent magnet 1, soft magnetic mover 2, ferromagnetic core 3, nonmagnetic bearing bushes 4, pole ring 5, coil 6 and spring 7. The actuator was studied in [4] using the magnetic circuit approach.

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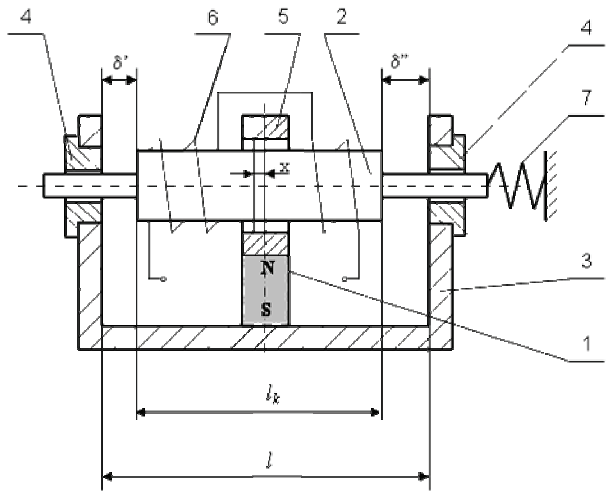


Fig. 1 – *Principal construction of the studied actuator.*

The coil 6 consists of two identical coils connected in series in such a way to excite magnetic flux in one direction. In this way, the flux created by the permanent magnet will be in the same direction with the flux created by the coil in one of the branches and in the opposite direction to the flux created by the other coil. This is the essence of the working principle of the actuator.

The magnetic system of the actuator is a typical differential system. A similar system can also be created by employing full rotational symmetry of the construction. In this case, though, the permanent magnet should be radially magnetized. In the studied construction, the mover is cylindrical but the permanent magnet is of block shape. Thus, a radially magnetized ring-shaped magnet is avoided.

The total stroke of the mover is 10mm (±5mm from the symmetry position). The active length of the mover is $l_k = 130$ mm, the internal size of the core is $l = 140$ mm. By moving the mover from the symmetry position, the two air gaps δ' and δ'' are changed. We will consider the position of the mover corresponding to displacement -5 mm when the left air gap δ' becomes zero, and $+5$ mm when the right air gap δ'' becomes zero.

Two types of permanent magnets were used for the study: NdFeB magnet with remanent flux density $B_r = 1.29$ T and coercive field $H_c = 979000$ A/m and a ferrite magnet with $B_r = 0.37$ T and $H_c = 273700$ A/m.

The m.m.f of the coils was assumed to be 840 A. The value of 1120 A which can be used for a lower duty cycle was also considered.

3 Finite Element Modelling

The actuator construction is such that it requires three-dimensional modeling.

The finite element method was used for modelling the 3D magnetostatic field of the actuator. The ANSYS® software package [5] was employed. The formulation with edge degrees of freedom for the edge magnetic flux was chosen. Computations were automated using the Ansys Parameter Design Language included in the program package.

The geometric model is shown in Fig. 2. Only elements important for the magnetostatic field were modelled, i.e. the non-magnetic bearing bushes 4 from Fig. 1 were not included in the model.

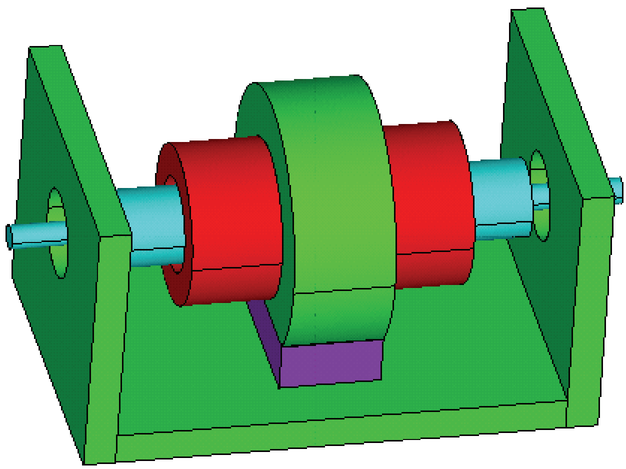


Fig. 2 – *Geometric model used in FEM analysis.*

Flux-parallel boundary conditions were imposed on the boundary of a buffer zone around the actuator. The buffer zone is not shown in Fig. 2.

The finite element mesh was generated using tetrahedral finite elements.

An example of the finite element mesh of the actuator without the buffer zone is shown in Fig. 3.

As a result of finite element modelling the magnetic flux density distribution and electromagnetic force acting on the mover were obtained.

3 Flux Density Distribution

The flux density distribution for the case of NdFeB magnet, left mover position and mmf $NI = 840\,\mathrm{A}$ is shown in Fig. 4.

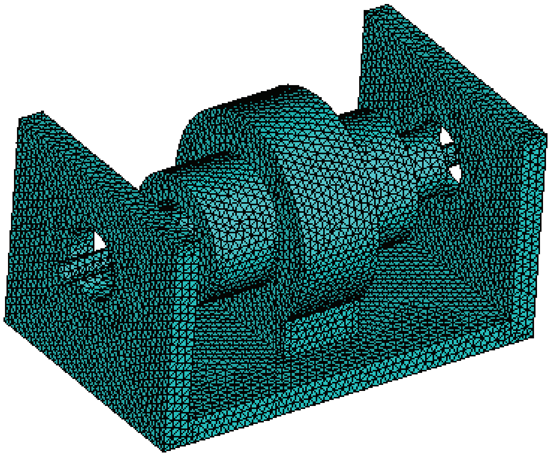
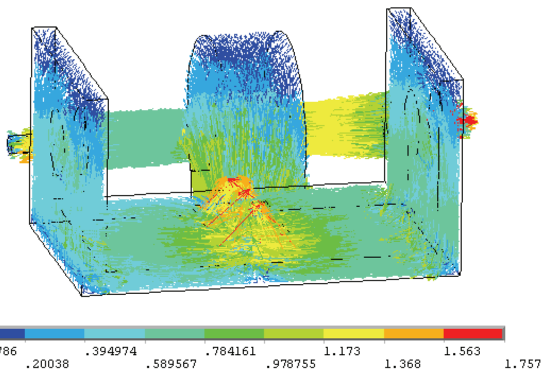
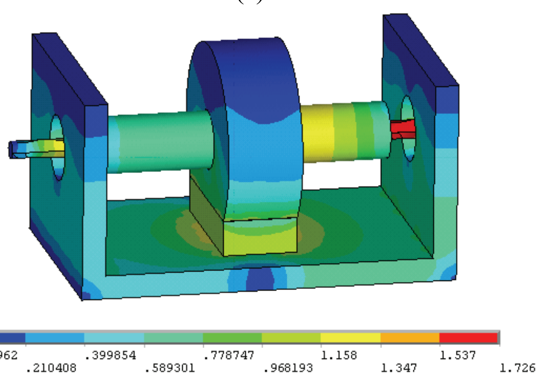


Fig. 3 – *Finite element mesh.*



(a)

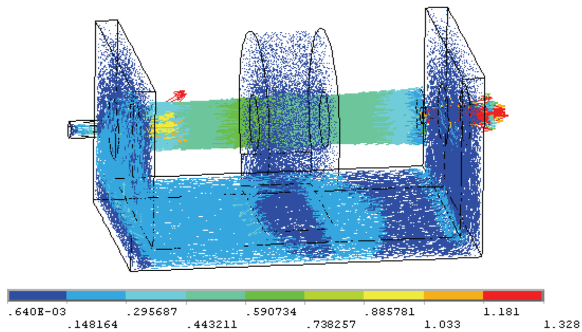


(b)

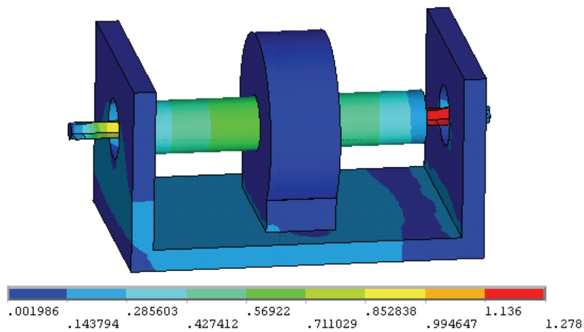
Fig. 4 – *Flux density distribution for an actuator with* NdFeB *magnet,*
$NI = 840\,\mathrm{A}$, $x = -5\,\mathrm{mm}$; (a) *vector plot*; (b) *colour map.*

The left branch remains unsaturated owing to the opposite directions of the fluxes due to the left coil and the permanent magnet. In the right part of the mover, the flux density is much higher.

For the same position (left one), the flux density distribution due only to the coils is shown in Fig. 5. In this case the permanent magnet is replaced by the same steel of the core.



(*a*)



(b)

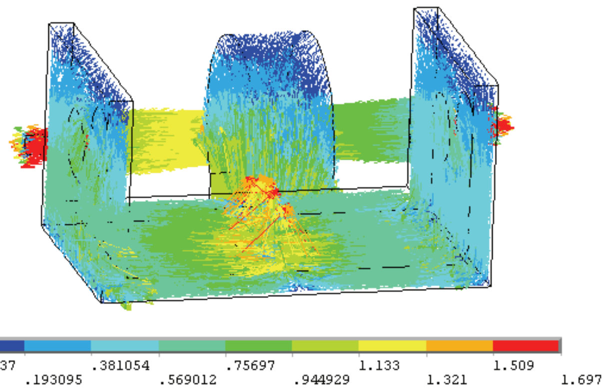
Fig. 5 – *Flux density distribution due to the coils only,*
$NI = 840\,\text{A}$, $x = -5\,\text{mm}$; (a) *vector plot*; (b) *colour map.*

In this case the left part is more saturated due to the mover position ($\delta' = 0$).

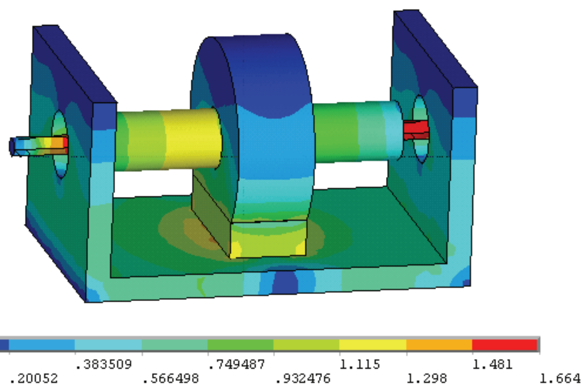
The flux density distribution due only to the permanent magnet for the same mover position is shown in Fig. 6.

It can be noticed that the NdFeB permanent magnet creates higher values of flux density than the currents in the coils, when acting separately. This determines the direction of the magnetic flux in the left branch (left part of the mover) to be the one of the permanent magnet flux. Here, optimization of the system can be considered in the future in terms of minimizing the flux in the left branch, which in turn will minimize the force in the back direction in the δ' gap.

Non-linearity of the core material also influences the flux balance and can be included in possible optimization.



(a)



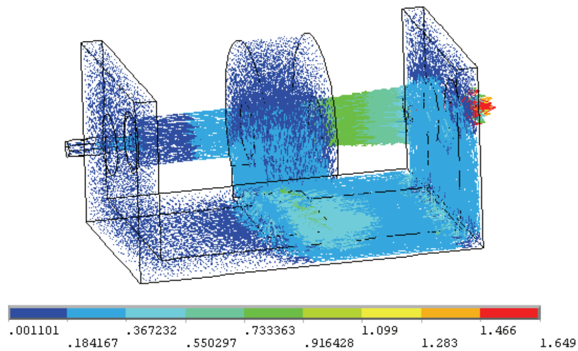
(b)

Fig. 6 – *Flux density distribution due to the magnet only*, NdFeB magnet, $x = -5\,\text{mm}$; (a) *vector plot*; (b) *colour map*.

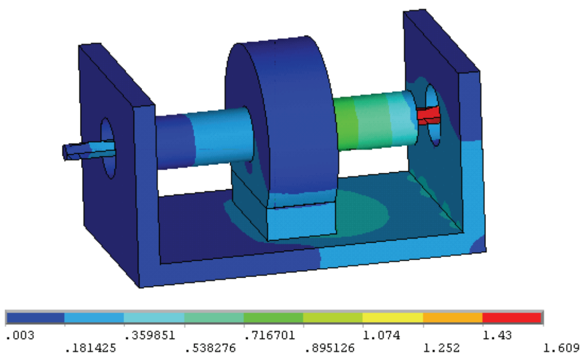
When a ferrite magnet is used in the construction, the flux density distribution for the left position of the mover is shown in Fig. 7.

In this case, the left coil dominates in the left branch over the magnet and the flux direction is opposite to the one in Fig. 4a. There is no demagnetization of the permanent magnet due to the flux from the left coil, as this flux goes along the right branch together with the one created by the right coil. The typical maximum value of the flux density in the mover is $0.8-0.9\,\text{T}$, while in the case of NdFeB magnet it is $1.2-1.3\,\text{T}$. Thus the magnetic system remains unsaturated as a whole, excluding some local values in the shaft of the mover, which are not important for creating the electromagnetic force.

For the actuator with NdFeB magnet, a study with a higher coil mmf of $1120\,\mathrm{A}$ was also carried out.



(a)



(b)

Fig. 7 – *Flux density distribution for an actuator with a ferrite magnet,* $NI = 840\,\mathrm{A}$, $x = -5\,\mathrm{mm}$; (a) *vector plot*; (b) *colour map*.

4 Electromagnetic Force

The electromagnetic force acting on the mover was obtained from the finite element analysis of a series of positions of the mover in order to cover the whole mover stroke.

The force-stroke characteristic of the actuator with NdFeB magnet is shown in Fig. 8 for coil mmf $840\,\mathrm{A}$ and in Fig. 9 for coil mmf $1120\,\mathrm{A}$.

The characteristics are almost linear, which is very suitable for obtaining different characteristics using different springs, as the springs also have a linear characteristic.

When comparing the two characteristics, it can be seen that for the left position of the mover (stroke $-5\,\mathrm{mm}$) the increase in the force is more than

50%, which can be explained with the above-mentioned flux balance in the left branch, while in the right position (stroke +5mm), the increase is about 15% and for this point there is saturation of the right branch.

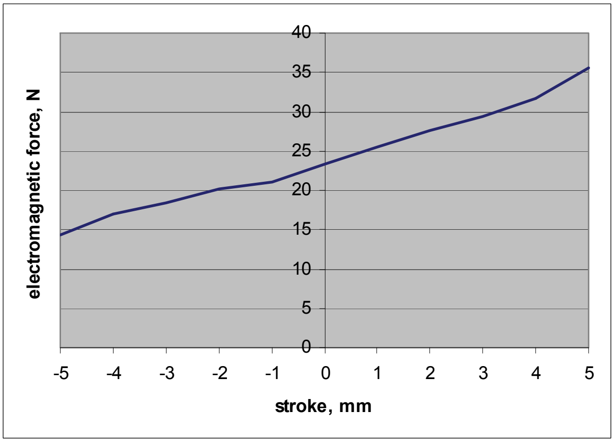


Fig. 8 – *Electromagnetic force for an actuator with* NdFeB *magnet,* $NI = 840\,\mathrm{A}$.

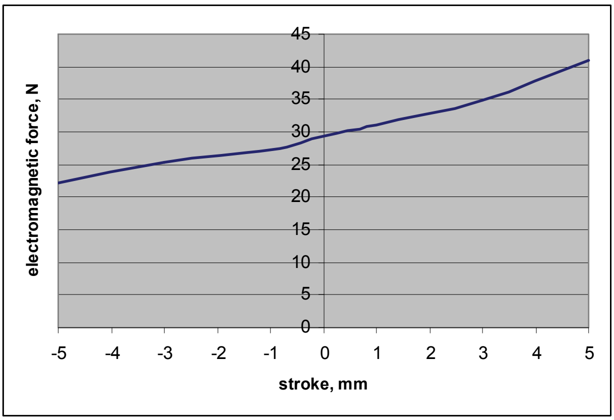


Fig. 9 – *Electromagnetic force for an actuator with NdFeB magnet,* $NI = 1120\,\mathrm{A}$.

The electromagnetic force due only to the coils is shown in Fig. 10. The characteristic is practically linear and symmetric regarding the symmetry position of the mover ($x = 0$). The values of the force are much lower than the ones of the whole actuator.

The force due only to the permanent magnet is shown in Fig. 11. The characteristic is also symmetric and of the same character, the values of the force are several time higher than the ones due only to the coils. It is worth noting that at the left mover position both force values in Figs. 10 and 11 have the highest magnitude of negative values, while when acting together (Fig. 8), the total force becomes positive, due to the above mentioned magnetic flux balance.

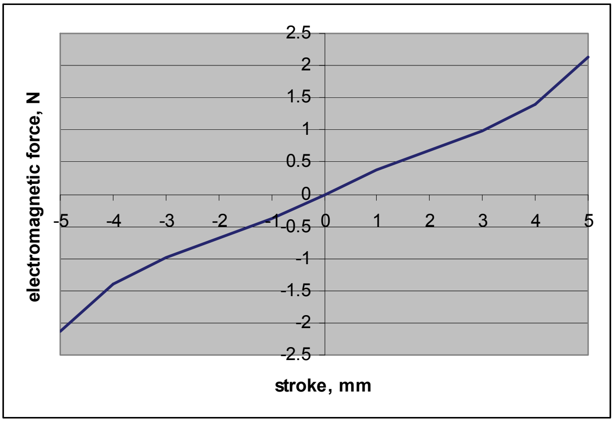


Fig. 10 – *Electromagnetic force due only to the coils,* $NI = 840\,\text{A}$.

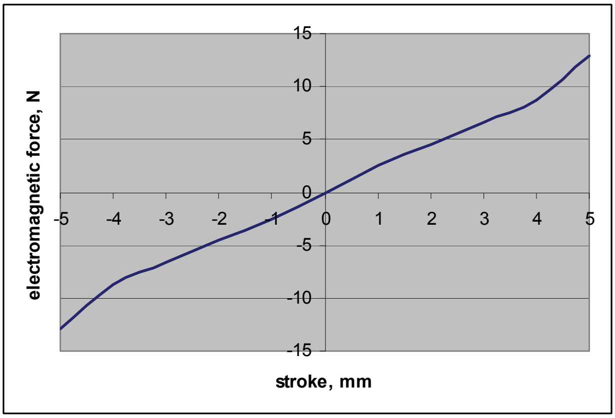


Fig. 11 – *Electromagnetic force due only to the permanent magnet,* NdFeB *magnet.*

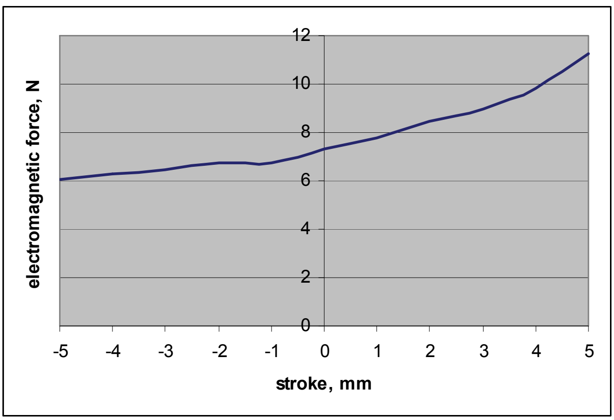


Fig. 12 – *Electromagnetic force for an actuator with a ferrite magnet,* $NI = 840\,\text{A}$.

Fig. 12 shows the force characteristic for an actuator with a ferrite magnet. It is not as linear as for NdFeB magnet and the values are several times lower.

5 Conclusion

The flux density distribution and electromagnetic force were obtained using 3D FEM for a permanent magnet linear actuator with a soft magnetic mover. Two types of permanent magnets were considered. The operating principle of the actuator was discussed on the basis of the obtained results.

Some directions of possible future optimization were outlined by specifying important factors and optimization criterion.

6 References

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