

AN INTEGRATED CAD ENVIRONMENT FOR DESIGNING AND SIMULATING DOUBLE SALIENT PERMANENT MAGNET LINEAR MOTORS

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ABSTRACT

Linear motors are widely used in uncountable industrial applications, where excellent dynamic behaviour, high position accuracy and repeatability, short settling times and smooth motions with variable speeds are obligatory. Therefore a novel modular double salient permanent magnet linear motor, which improves a well-established motor type, may be of real interest.

In this paper a user-friendly (a graphical used interface co-ordinated) fully integrated CAD environment for designing and simulating such type of motors is presented.

Simulated results prove the usefulness of both the design procedure and programs for those professionals who would like to design and simulate such a motor, or a similar one.

1. INTRODUCTION

Direct-drive linear motors have a lot of benefits, as simplicity, efficiency, and positioning accuracy [1]. They also replace ballscrews, gear trains, belts and pulleys, all of these being limiting factors for engineers trying to improve the linear drive system's performance. Therefore these motors are ideal for applications that require high position accuracy and repeatability. Such a direct-drive linear motor is the widely used hybrid linear stepper motor [2].

This motor has some well-known disadvantages. Its main drawback is the very great attractive normal force generated by all the poles between the platen and mover. This force 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. Although this force cannot be totally

eliminated in the case of flat linear motors, there are several attempts to reduce it as much as possible [3].

One of the best choices to solve this problem is the modular double salient permanent magnet linear motor proposed by the authors [4].

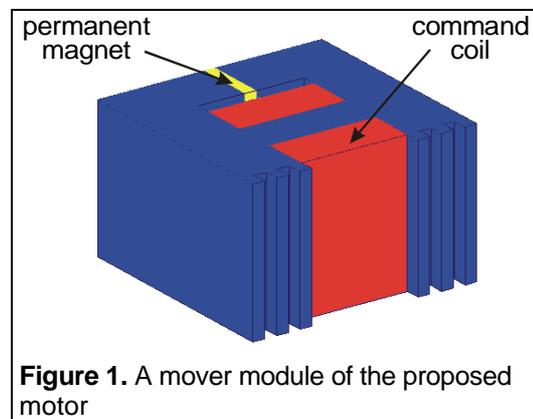
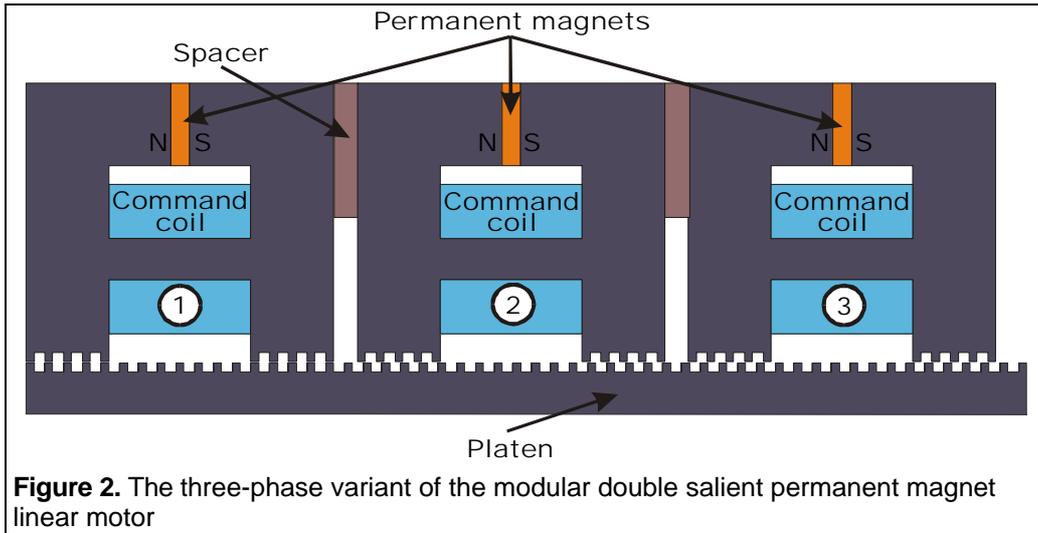


Figure 1. A mover module of the proposed motor

The novel motor is composed of mover modules (shown in figure 1), each having a permanent magnet. The magnetic flux generated by the permanent magnet can be directed by the command coil to pass or not to pass through the air-gap. When the command coil of the module is energised, the module generates a significant tangential force. When it is inactive, the magnetic flux will pass through the core branch in parallel with the permanent magnet, due to its less magnetic resistance than that of the air-gap. In this case there is neither braking, nor attractive force produced.

Linear motors having different characteristics can be assembled using these modules. By energising the command coils sequentially with current pulses, the mover can travel linearly in both directions. In such a way the motor behaves like an electromagnetic incremental motion actuator, which converts sequential command current pulse inputs in linear motion.



The distance between two neighbor modules and the teeth pitch prescribe the step length of the motor. By increasing the number of the modules placed in the same position relatively to the platen teeth the produced total tangential thrust force can be multiplied. This way the linear motor assembly can be easily designed and constructed for every specific application. It also allows an optimal adaptation to the particular application and makes the motor capable of satisfying extreme requirements (for example in applications where fast and accurate moves under heavy loads are required).

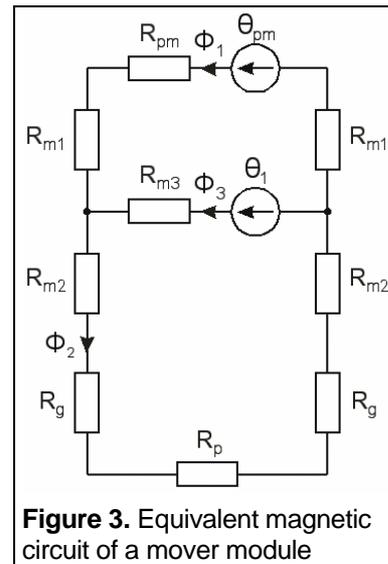
A very advantageous motor variant is that having three modules (shown in figure 2), because it can be simply supplied from a low cost standard three-phase compact converter connected to an intelligent speed control unit.

2. DESIGN PROCEDURE

The modular double salient permanent magnet linear motor's design presents some specific aspects because of the complex toothed structure and of the requirement to take into account the iron core saturation and permanent magnet operating point change. The design algorithm and the afferent computer program elaborated by the authors mainly solve these problems, offering a useful tool for designers.

The proposed design procedure is based on several relationships obtained from a simplified analytical motor model [5] and on some existing experience in this field. The analytical model basics of the motor is a simplified magnetic equivalent circuit (shown in figure 3) of the mover module and of the platen segment under it. It

consists two MMFs (θ_l and θ_{pm}) of the command coil and of the permanent magnet. There are 9 reluctances in the circuit: R_{pm} of the permanent magnet, R_{m1} and R_{m2} of the pole, R_{m3} of the core branch with the command coil, R_g of the variable air-gap and R_p of the platen segment under the mover module.



In the first stage of the design procedure the following required design inputs must be prescribed depending on the application in which the motor will be used:

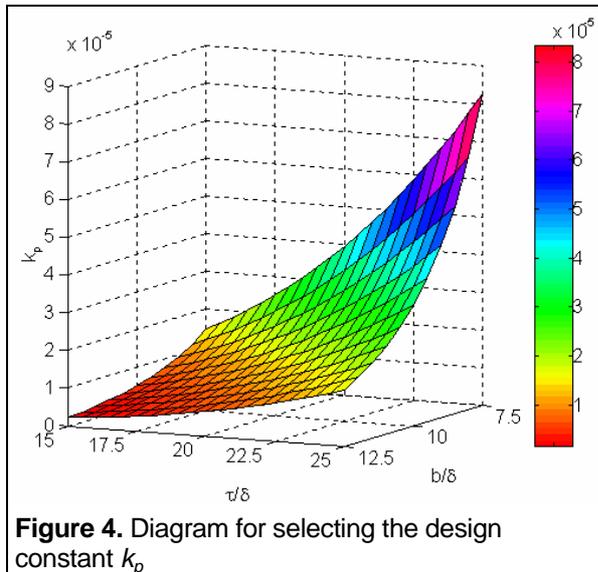
- i) Number of modules (N)
- ii) The maximal tangential force to be developed by the motor (F_{tmax})
- iii) The resolution of the positioning (the step length x_j)
- iv) The length and the width of the running track (w_r and l_r).

The second stage is the main part of the design procedure. Here are established all the motor's dimensions. At the beginning the sizes of the toothed air-gap structure must be computed: the tooth pitch (function of the imposed positioning accuracy) and the air-gap length (that must be as small as mechanically possible). The selection of the best tooth geometry is very important, too.

The next step consists in choosing the active ferromagnetic materials used for the motor. Extremely important is the permanent magnet selection, the most expensive and sensitive assembly of the motor. The imposed temperature rise in the mover and the motor cost to performance ratio must be taken into account. Rare-earth magnets are needed to meet the high force per unit volume necessities of the motor. The magnet working point (B_{pm}, H_{pm}) on the straight demagnetisation characteristic throughout the second quadrant must ensure the desired flux density levels in the mover and platen cores. The permanent magnet dimensions can be determined by computing its minimal active surface and thickness:

$$S_{pm_{min}} = k_p \frac{F_{t_{max}}}{2B_p B_{pm}} \quad (1)$$

where B_p is the imposed flux density in the poles. The designing constant k_p depends on the teeth pitch, respectively the slot width to air-gap length ratio (τ/δ and b/δ). It can be easily determined from the three-dimensional diagram shown in figure 4.



In a similar way can be determined the length of the permanent magnet:

$$l_{pm} = k_x \frac{B_p B_r}{H_c (B_r - B_{pm})} \quad (2)$$

where B_r and H_c are the residual flux density, respectively the coercive force of the selected permanent magnet. The k_x dimensioning constant can be chosen from a 3D diagram similar to that shown in figure 3.

The obtained dimensions of the magnet have to be rounded to actual data sheet values. After this a short iterative optimisation have to be made in order to find out the minimum volume of the magnet that is able to generate the required forces.

The control coil design have to be made as a function of its MMF ($w \cdot I$). It must be so great as to force all the permanent magnet's flux through the poles and the air-gaps. Also in this case a simple optimisation process can be applied. As numerous products of w and I can give the same MMF, it must be chosen that combination which will produce the less $I^2 R$ loss in the command coil. This way both the electrical input and thermal dissipation of the command coil are minimised.

Next the sizes of the command coil must be determined. The coil length must ensure a distance equal to an integer multiple of the teeth pitch between the two poles. As the coil length and width imposes the yoke length, respectively the pole height, it is very important to choose in an optimal way the ratio of the two coil sizes. Beside this the coil width to length ratio must be prescribed in a manner to reduce as much as possible the leakage flux of the coil. As in this case there are also several possibilities to define the two main sizes of the command coil and there are three different requirements to fulfil, an optimisation process must be applied in order to define the best coil width to length ratio. Since the coil sizes impose the two of the main dimensions of the mover core, the most significant result of this simple optimisation can be the minimisation of the total core volume.

One of the most sensitive stages of the motor's design is the sizing of the core branch on which the command coil is placed. When the module is inactive, all the flux generated by the permanent magnet has to pass through this core element. While the command coil is energised the command flux produced has to concentrate the entire permanent magnet flux to pass through the poles and air-gaps. The analytical computation of this core branch is quite difficult due to its dependence of several items pending on other

motor components. In this case an iterative field computation process was adopted in order to find out the best cross-section of this core branch (its length is imposed by the length of the command coil).

The rest of the sizes of the mover module and of the platen are computed just like in the case of the classical hybrid stepper motor [2].

As it was stated out, the step length of the motor depends also on the number of modules coupled to form the mover (N). Due to this is very important to ensure the required distance between two mover modules. Beside this the spacers placed between the modules have to avoid direct magnetic coupling through the leakage fluxes of the two modules. In conclusion the following expression must be considered for the spacer length:

$$l_{sp} = k\tau + \frac{\tau}{N}, \quad k \in \mathbb{N}, k \geq 2 \quad (3)$$

This was the last part of the design algorithm. Next the practical way of implementing this design algorithm will be presented.

3. DESIGN AND SIMULATION PROGRAM

All the design and simulation programs are integrated into a single, user-friendly CAD environment based on MATLAB/SIMULINK. The basic idea in creating this software tool was that the same mathematical motor model is used in both the sizing and simulation stages of the design process.

All the operations are co-ordinated by a graphical user interface (GUI) with very friendly pull-down menus and dialog boxes (see figure 5).

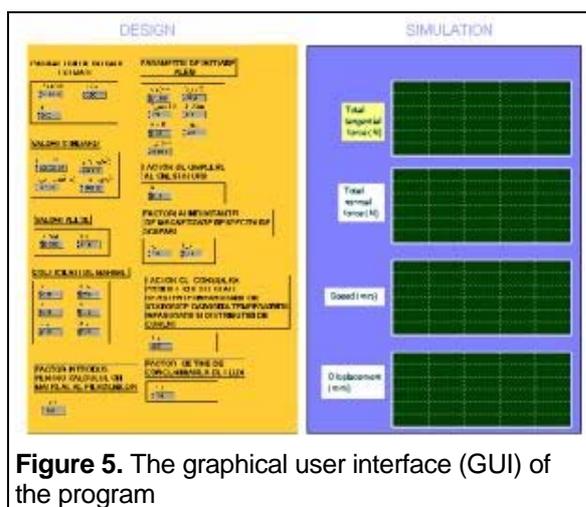


Figure 5. The graphical user interface (GUI) of the program

The basic design program was written in MATLAB [6]. This computing platform was selected because it features several benefits as interactive mode of work, immediate graphing facilities, numerous built-in functions and the possibility of adding user-written functions. It also has several functions for creating user friendly graphical user interfaces (GUI) and possibilities to interact with SIMULINK, the MATLAB toolbox for simulating dynamic systems.

This way all the design relationships were easily implemented. The design input parameters and a few parameters (as air-gap length, teeth length to teeth pitch ratio, etc.) can be fixed by the user in easy-to-operate edit boxes from the graphical user interface. The permanent magnet and the ferromagnetic materials needed for the motor are selected from three pop-up menus containing a vast list of materials together with their main characteristics. When a material is chosen, its characteristics are loaded automatically in proper variables of the design program.

The above presented optimisation tasks are carried on by several user-defined functions. In this stage of our research these functions are not completing a complex authentic optimisation process, but their simple algorithms allow to take into account all the given possibilities and to choose the best solution for a given problem. Of course in the future it will be necessary to elaborate a more sophisticated, general optimisation of the design process.

In the last part of the program the electromagnetic checking of the motor is performed. This analysis is performed using the analytic computation of the magnetic flux linkages through the motor based on the equivalent magnetic circuit of the motor.

The obtained results (mainly the dimensions of the motor) are displayed in edit boxes. Beside this the program generates a diary (saved in a text file) of the entire design process.

All of the characteristics of the designed modular double salient permanent magnet linear motor can be checked by means of computer dynamic simulation based on the simplified circuit-field mathematical model of the motor [5].

The model was implemented using the MATLAB/SIMULINK environment. SIMULINK is a toolbox of MATLAB. It is one of the most fervently used a graphical user interface based software for modeling, simulating, and analyzing both linear and nonlinear dynamical systems [7].

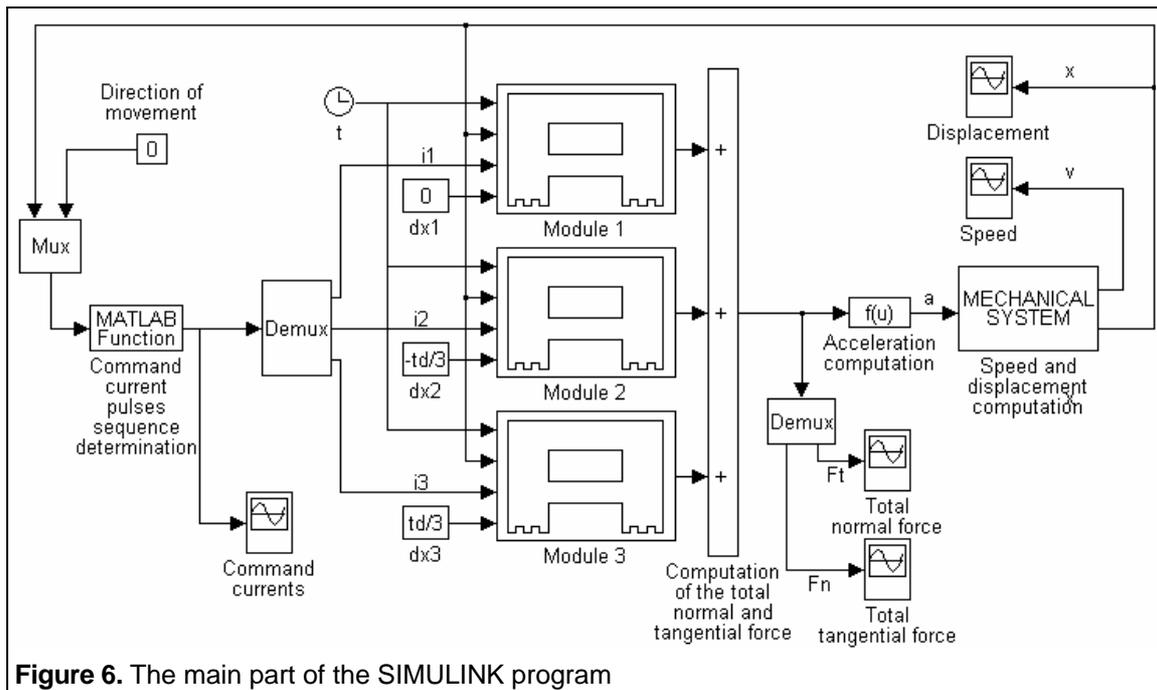


Figure 6. The main part of the SIMULINK program

The main part of the simulation program is shown in figure 6.

The simulation program can be used beside this also for simulating diverse dynamic regimes of the motor. Combined with a simple MATLAB program it can be used also for the thermal checking of the motor. This can be performed by simulating a long-term cyclic movement of the motor and computing the thermal rise in different motor parts.

4. RESULTS

The above presented design procedure and programs have been used to design several types of motors obtained by combining different number of mover modules.

The dimensions of a designed mover module

obtained for the following input design data:

$$\begin{aligned} F_{t_{\max}} &= 30\text{N} & x_i &= 0.5\text{mm} \\ l_r &= 200\text{mm} & w_r &= 85\text{mm} \end{aligned} \quad (4)$$

are presented in figure 7. A sector of the toothed air-gap sector is presented enlarged

A four step long displacement of the motor was simulated using the program presented previously. The obtained results are displayed on the graphical user interface of the main program using SIMULINK Scope blocks. All the results were also exported to MATLAB workspace in order to be able to save them in readable text files and to make a better graphical processing of them.

The most significant results, the plots versus time of the command currents, total tangential

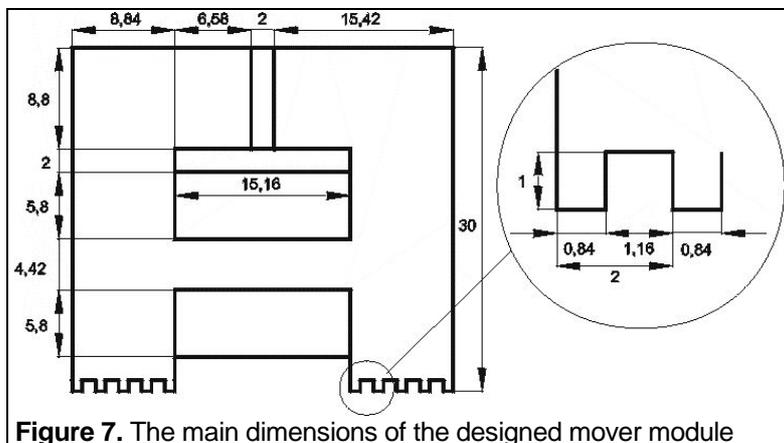


Figure 7. The main dimensions of the designed mover module

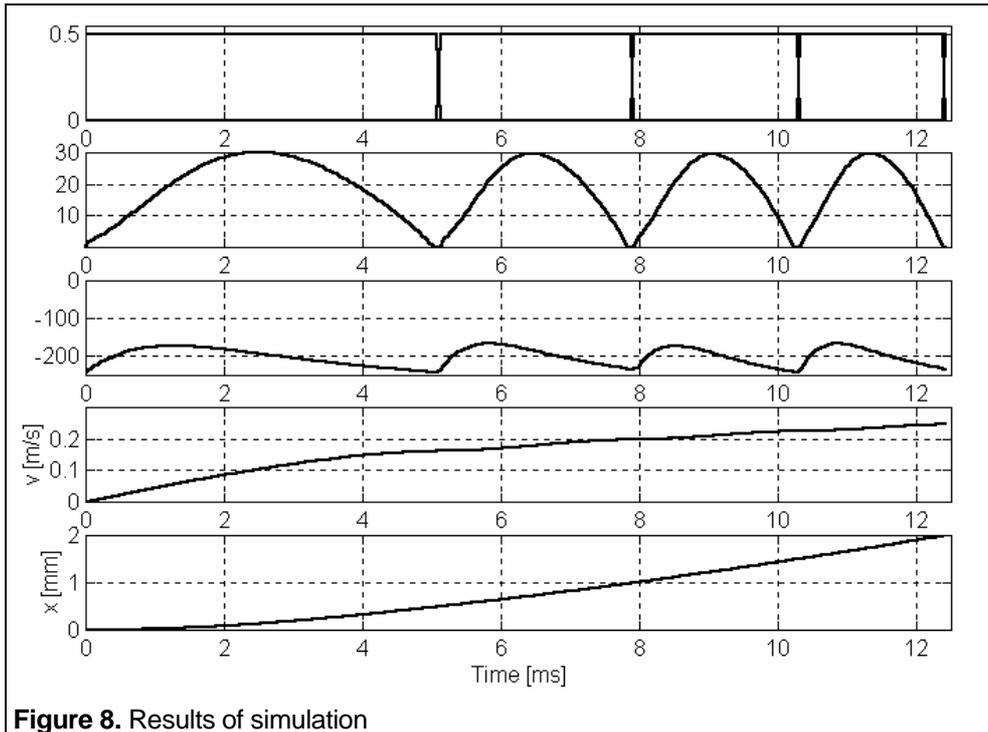


Figure 8. Results of simulation

and normal force, speed and displacement are presented in figure 8.

5. CONCLUSIONS

This useful software tool is specially tailored for the design and simulation tasks to be performed by the designers. Any changes in the design parameters can be made easily and quickly, so the whole design procedure can be executed in the shortest time possible. The whole design operation is invisible for the users, who has only the simple tasks of introducing the input design data, of selecting the permanent magnet and the ferromagnetic materials type and of choosing the simulated regime of the designed motor.

Therefore this CAD tool surely will meet the demands of the professionals who would like to design and simulate such a motor, or a similar one.

As it was already stated out, in the future it will be necessary to elaborate a more sophisticated, general optimisation algorithm of the design process in order to reduce both the permanent magnet and the core volume. This way the motor's dynamic performances can be improved considerably.

Beside this a connection to a numeric field analysis program must be made in order to perform the final electromagnetic checking of the

motor using a more accurate finite elements method based program package.

6. REFERENCES

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