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Experimental verification of the one-phase linear actuator with permanent magnets for robotic system applications

Abstract

In this paper an experimental results of a static and transient characteristics of the linear motor is to be presented. The linear motor consists of the one cylindrical unmovable coil surrounded by a soft ferromagnetic case and a moveable core made from sequence of ferromagnetic and permanent rings. The model of the linear motor is to be presented with mechanical, electrical and magnetic consideration. At the end of this paper the experimental results are presented with focus on static magnetic force and transient response for a series input voltage steps. The aim of this investigation it was to check the static and dynamic characteristics and assume the usability for application in robotic systems.

Keywords: Multidisciplinary modelling, electromagnetic linear actuator, permanent magnet linear motor, robotics.

1. Introduction

Electromagnetic actuators are commonly used in automation and robotic application. The main advantages of the electromagnetic linear actuators are the simple design structure, the fast response for input signal, a possibility to achieve a high linear acceleration and a low cost of maintenance. Moreover, a linear motion is a natural output, so there is no need of any mechanical transmission. Because there is no gearing the only friction points are the required linear guides and the lifespan can be relatively long [3].

Among many specific expectations, the linear motor for robotic applications should be capable of generating significant force. It is often desirable to remain position after turn off the power supply. What is more, great simplification the drive mechanisms is crucial for robotic systems [4]. That is why the one-coil actuator with moveable core constructed from many section of permanent magnets and ferromagnetic rings has been taken under consideration. By using permanent magnets, much higher force-to-volume ratios can be acquired than using electromagnets and better drive performance can be obtained. The control process can be carried out by the open loop control if permanent magnets are used. The force exerted between the permanent magnets and the coil was first calculated theoretically and then verified empirically.

Although motors with two or more coils (phases) have lower oscillation after transient response for a input voltage step the one-coil actuator have been taken under consideration, because it is easier to control and the process of validation of the simulation model can be more convenient. The basic scheme of the one-phase linear actuator with permanent magnets has been depicted in the Fig. 1.

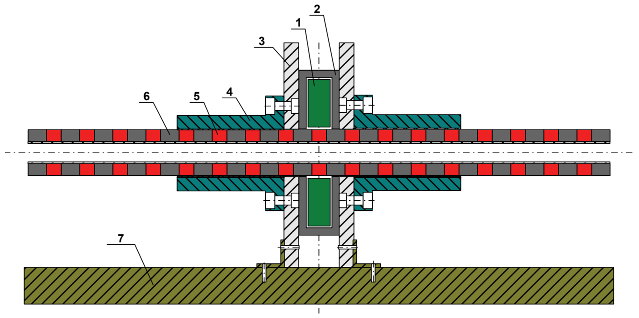


Fig. 1. The scheme of the one-phase permanent-magnet tubular linear motor, 1-coil, 2-ferromagnetic case, 3-holder, 4-linear bearing, 5-pemanent magnet, 6-ferromagnetic ring, 7-fixed link

To complete an adequate mathematical model the following actions have been taken:

1. Definition and specification of the object and its environment. On the basis of designation of the model, determination its accuracy and scope of validity.
2. Identification of all processes and relations in the object.
3. For each phenomenon define assumptions and simplifications. Taking a decision whether the phenomenon is space distributed or discrete. If distributed, assuming continuity, symmetry and number of space dimensions (1D, 2D or 3D)
4. Definition of mathematical relations.
5. Decision on how to solve the model. As the rule, it comprises nonlinear partial or ordinary equations, so computer programme is necessary. A commercial package would be the best choice, but in the case of many various energy streams involved (e.g. Multiphisics case), one does not find any commercial code and one must device a special programme.
6. Verification the code; validation the model.

2. Simulation model

The magnetic energy from the coil and from the permanent magnets are coupled, and the interaction depends also on the position of the core. A distribution of the magnetic field is not uniform in the air gap so it must be modelled as a continuous in space. If the core velocity is not high, the air pressure resistance may be omitted [1]. Also electrical properties may be accepted as discrete in space, as the current changes in coils are comparatively slow. As the motion process of the core is short, the temperature increase is small and the process may be assumed as an isothermal, and all material parameters to be constant. To summarize, there are many nonlinear phenomena, and they are strongly coupled [2]. The mechanical equations have been implemented in the Matlab package and the Maxwell equations have been used in the ComsolMultiphysic's package. Two programs are working together respectively. In the Fig. 2 the interaction between mechanic, electric and magnetic phenomena are presented with division to the two program packages. In the Fig. 2 an interchange of data between the two programs is shown.

For the linear motor dynamic evaluation the two (electromagnetic and mechanic) equations have been taken under consideration:

$$u(t) = R \cdot i(t) + \frac{\mathrm{d}\Psi(t)}{\mathrm{d}t} \tag{1}$$

$$m \cdot \frac{\mathrm{d}^2 z}{\mathrm{d}t^2} = F_e - F_t - F_{load} \tag{2}$$

where:

$u(t)$ – voltage supplied to the coil, V;
R – Ohm resistance of the coil, Ω;
$i(t)$ – current in the coil, A
Ψ – magnetic flux in the air gap, Wb;
z – core displacement, mm;
m – core mass, kg;
F_{load} – additional resisting force;
F_e – electromagnetic force;
F_t – friction force;
t – time, s;

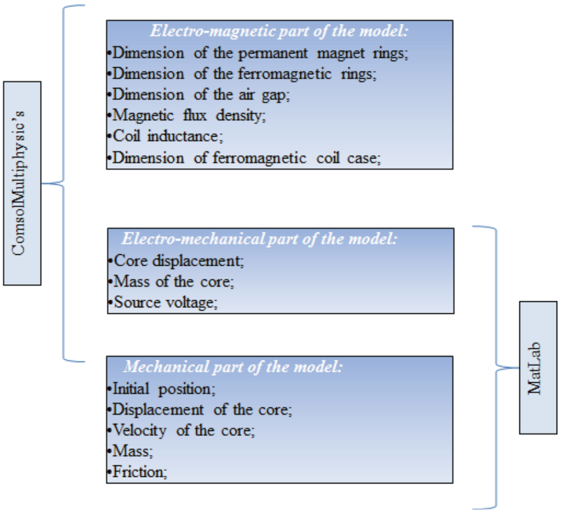


Fig. 2. The interaction between mechanic, electric and magnetic phenomena with division to the two programs (MatLab and ComsolMultiphysic's)

The magnetic flux Ψ is a sum of two components:

$$\Psi = \Psi_m + \Psi_i \tag{3}$$

where:

Ψ_m – magnetic flux from permanent magnet rings;

Ψ_i – magnetic flux from the coil.

The magnetic flux has been computed in two dimensional simulation model in the ComsolMultiphysic's package (Fig. 3). Because of the model symmetry, only a half of the device has been taken under consideration [5, 7].

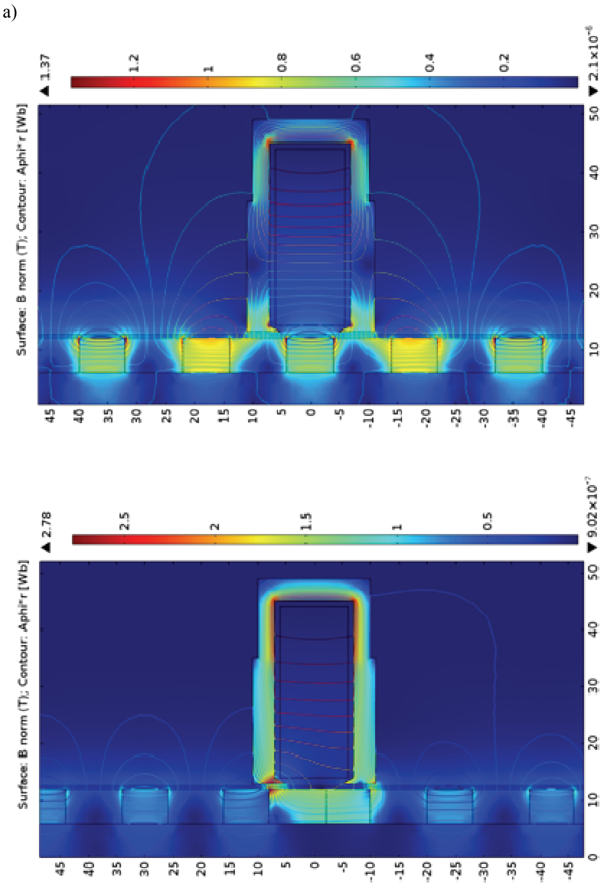


Fig. 3. Magnetic flux calculation in the FEM (finite element method) model: a) ferromagnetic coil case between permanent magnets; b) ferromagnetic coil case at the edge of the permanent magnets

The value of magnetic flux (Fig. 3) as a function of the core displacement and as a function of the coil current have been implemented to the dynamic equation (4) and the simulation model has been completed in MatLab-Simulink package (Fig. 4 and Fig. 5).

$$\begin{cases} \dfrac{\mathrm{d}i_k}{\mathrm{d}t} = \dfrac{1}{\dfrac{\partial \Psi_k(i,z)}{\partial i_k}} \cdot \left(u_k - R \cdot i_k - \dfrac{\partial \Psi_k(i,z)}{\partial z} \cdot v_z \right) \\ \dfrac{\mathrm{d}z}{\mathrm{d}t} = v_z \\ \dfrac{\mathrm{d}^2 z}{\mathrm{d}t^2} = \dfrac{1}{m} \cdot \left(F_e(i_k, z) - K_d \cdot v_z - K_s - F_{load} \right) \end{cases} \tag{4}$$

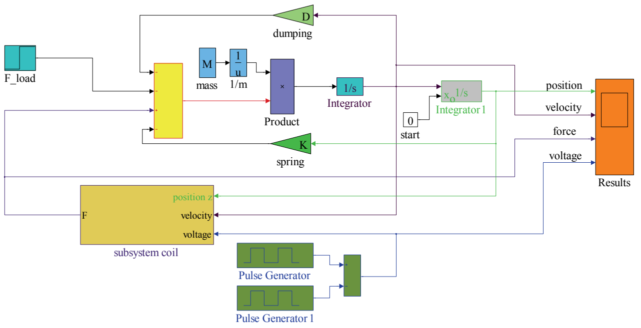


Fig. 4. Dynamic model of one the one-phase actuator with magnetic field value implemented in the coil subsystem

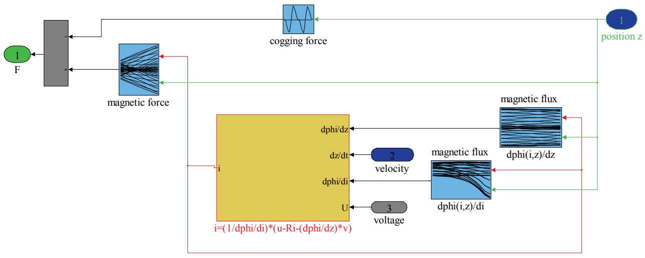


Fig. 5. The coil subsystem with magnetic field values evaluated from partial differential equations (resolved in ComsolMutiphysic's)

3. Experimental results

The elements of the laboratory model of the linear actuator are presented in the Fig. 6.

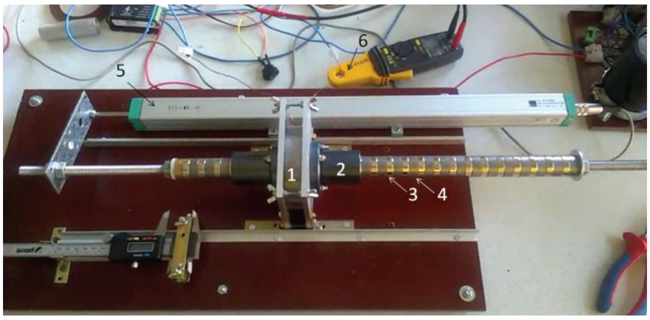


Fig. 6 The laboratory linear actuator permanent-magnet tubular linear motor: 1-coil with ferromagnetic case, 2 - linear bearing, 3 - permanent magnet ring, 4 - ferromagnetic ring, 5 - position sensor, 6 - specialize current sensor "center 223"

The coil was made from 300 copper wires with the diameter of 1 mm. The coil resistance is equal to R=2.1 Ω, and the inductance is equal to L=5.5 mH. The coil was supplied from the brushless PWM servo amplifier from the Advance System Control company.

Static characteristics

In the Figure 7 the value of coaxial magnetic force between permanent magnets and ferromagnetic case as a function of core displacement is depicted. The coil was unsupplied and the electromagnetic force was evaluated by the force sensor KMM20. The distance 18 mm between each permanent magnets was divided into 37 parts for static measurement of force in each point. The maximal force from permanent magnet is approximately 40 N for the configuration presented in the Figure 3a. This kind of force generates additional oscillation but on the other hand if the power supplier unit unpredictable failed it helps to stop accelerated core. Moreover, desired position can be maintained after the power unit is switch off.

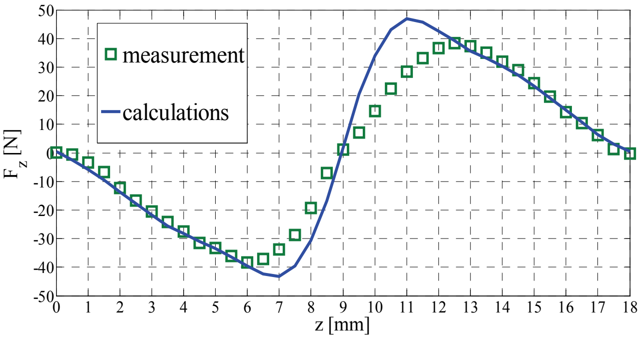


Fig. 7. The magnetic force between permanent magnets and ferromagnetic case when coil is switch off

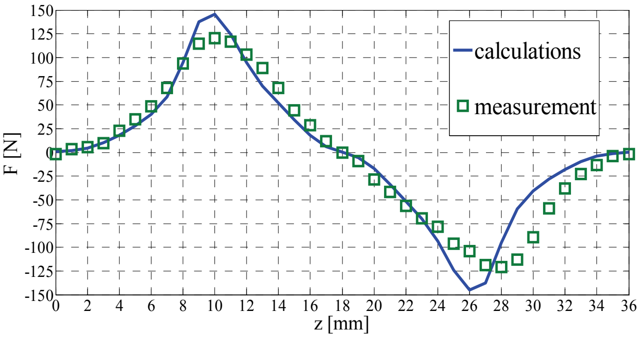


Fig. 8. The magnetic force between permanent magnets and ferromagnetic case for coil supplied with the static voltage value

The value of coaxial electro-magnetic force between permanent magnets and the supplied coil with the ferromagnetic case is depicted in the Figure 8. The interaction between magnetic field changes the equilibrium position. This can lead to smooth movement if proper current control algorithm is going to be implemented.

Dynamic characteristics

The dynamic characteristics have been achieved for the core displacement in time, as a function of many different time voltage impulses supplied to the coil. The coil has been supplied by voltage square signal with length time vary from 0.3 to 12 seconds (Figure 9). After each voltage step the next one has the same amplitude and the same time, but inverse polarity. The core has been pulled and pushed alternately sixteen times.

In the robotic system application the moving range can depend only on the permanent magnets and ferromagnetic rings quantity.

In order to measure the core displacement in time, the linear potentiometer sensor has been used. Based on preliminary calculations of current, it was determined that a 10 A current sensor would be adequate to measure the coil current. The specialize current sensor “center 223” has been used. All measurement data have been gathered by real-time dSpace package with using analogue to digital converters.

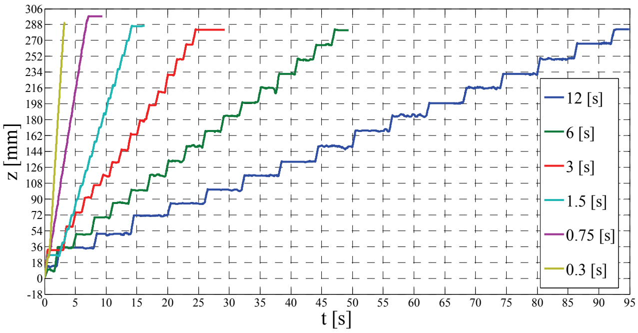
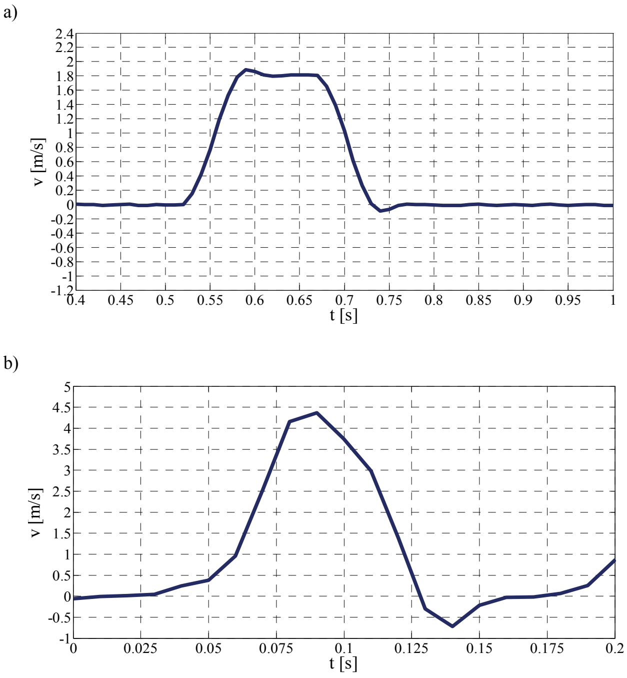


Fig. 9. The displacement of the core as a function of time for different value of impulse length

The step response of a linear actuator is a useful tool to gauge its performance in point-to-point manoeuvrability. Other important characteristics are the percent overshoot, settling time, and steady-state error. In the Figure 10 a two examples of the core displacement as a function of time for different value of coil current are presented. It can be seen that after each input voltage step the core position is changing proportionally to the length of the both: the permanent magnet and ferromagnetic ring dimension.


a)

b)

Fig. 1. The core velocity step response as a function of time for current in the coil: a) 5 A, b) 8 A

Due to low friction the dynamic response on the input step voltage depends on the magnetic and mechanic inertia. The mechanic inertia can be easily changed due to the length and mass of the core. In the Figure 10 the one step of the moving core is presented for different value of the impulse time and current value in the coil. The core can achieve the velocity of 1.8 m/s during 0.02 second (Fig. 10a) or even the 4.3 m/s for the higher current and shorter time of the voltage impulse (Fig. 10b). The next important feature is to keep the core position until the next step voltage with inverse polarity. There oscillation and overshoot are relatively low-intensity, mainly because of the magnetic force between permanent magnets and ferromagnetic case of the coil.

4. Conclusions

In this paper, the design, construction, and testing of the one-phase linear actuator with permanent magnets moving core were discussed. Mathematical model of transient processes for computer simulation purposes has been presented with a few various energy streams consideration. For the non-uniform energy density field in the 3D space partial differential equations have been applied. Because of the model symmetry and the long simulation computation time only half of the electromagnetic device has been taken under consideration [6]. For the object under consideration a multidisciplinary model combined the finite element analysis with computational engineering tools and applications such as the control system design, signal processing and dynamic simulations. It can be observed much output information in specific points of the device as a function of input construction data. In the future investigations the multidisciplinary model will be used for the control algorithm optimization process.

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