Static and Dynamic Characteristics of a Double Armature DC Linear Motor

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Abstract

A brushless and slotless dc linear motor employing a movable set of neodymium-boron-iron type magnets is discussed in this paper. The motor can be used as a linear stepping motor as well, due to its unique topology. The flux density at specific points and the static force along the travel length of the motor were measured. A 3D finite element analysis of the flux distribution and of the static force were carried out. The dynamic characteristics such as velocity, output power and efficiency for various conditions were measured.

Keywords: linear motor, dc motor, permanent magnet, static force, dynamic characteristic

1. Introduction

There are advantages in some applications when using direct linear drives instead of converting rotary motion into linear movement. The linear motor can be more reliable and compact, presents better dynamic response, and requires less maintenance when replacing drives based on rotary motors and other linear actuators, e.g. pneumatic and hydraulic ones¹⁻⁵. This paper describes the development of a large novel voice coil linear dc motor featuring a double square armature. Permanent magnets with maximum energy product of large value act as field sources and surround three sides of each armature, thus producing considerably large force-to-mass ratios. This motor is classified as a short secondary type, and may be used as a slotless linear stepping motor.

An increment in the maximum permeability of the mild steel, the linear motor is made from, was achieved by annealing. It resulted in a 5% increase of the developed force. An analytical process was developed to find an optimum shape for the slider back iron. The main constraint in this optimisation process was the saturation induction of the material the back iron is made of. A finite element analysis produced results that validated the analytical optimisation process.

In order to improve the understanding of the linear motor and validate its theoretical and numerical results, a comprehensive series of tests was carried out. These tests were conceived to measure various parameters under different operating conditions. The linear motor was driven by an electronic system which controlled each coil section of the two armature windings to provide conditions for dynamic tests.

2. Principles of operation

The double armature homopolar brushless dc linear motor was conceived with the main idea of making a linear motor with improved sensitivity⁶. The approach chosen was to surround the sides of the armature with high maximum energy product permanent magnets. This resulted in an enlarged active length of the armature conductors. The

linear motor had to be provided with a closed magnetic circuit for the magnetic flux supplied by the permanent magnets. In this case the solution was found by using a second armature to complete the magnetic circuit. The external side of each armature was not encircled by any permanent magnets, thus the terminals of the coil sections could be easily accessible for connection to the power supply as shown in Fig.1. The slotless rectangular shaped armature core made of two long and two short bars of heat-treated mild steel uses a double armature configuration. Gaps have been made by nonmagnetic material along the armature magnetic circuit. They avoid magnetic saturation and minimise the magnetic pull end-effect. Furthermore, a better motor time constant can be achieved with them. The topology of this motor is quite different from those presented by Honds and Meyer⁷. The armature winding is distributed along the long bars. On each bar, there are fourteen independent six-layer 159-turn coil sections

Fig.1 Perspective view of double armature homopolar brushless d.c. linear motor

wound with 0.5 mm diameter copper wire with polyurethane insulation. Each coil section is 15.3 mm in length and fed with switched currents. There is physical displacement of the coils of one bar with respect to the ones on the other. If the length of each section is $2a$ in z -direction, the distance between two consecutive coils, one on the first bar and the other on the second one, is a , which is the displacement step of the slider as well. The slider moves along the travel length supported by a pair of linear bearings and two parallel shafts. Hanaoka et al⁸ used V-wheels instead of linear bearings in their motor.

The cross-section of the slider and the armature are shown in Fig. 2. The five permanent magnet blocks are arranged in such a way around the armature bars a and b that the excitation flux converges to bar a through three lateral sides from the magnet blocks placed opposite to the air gaps. The magnetic path of each permanent magnet closes through the slider back iron and the armature bars. The model of the linear motor presents symmetries with respect to zy and zx planes. On the other side, the excitation magnetic flux diverges from bar b towards the permanent magnet pieces placed opposite to the air gaps.

Fig. 2 Frontal view of the slider

2.1 Force, Sensitivity and Power

The assessment of the longitudinal force initially disregards the existence of any reluctance force and leakage flux. The equation given below is derived from the Lorentz's law and is employed to obtain a scalar expression for the force the linear motor can develop.

$$\bar{F} = \int_V \bar{B} \times \bar{J} dV \quad (\text{N}) \quad (1)$$

where V is the volume of the part of the armature winding that effectively produces the force on the slider, in other words, it comprehends the conductors on one armature bar that are subjected to the air gap flux density $\bar{B}$. As $\bar{B}$ is

perpendicular to the current density, $\bar{J}$ Eq (1) assumes a scalar form

$$F = \int_V B J dV \quad (\text{N}) \quad (2)$$

The volume of the active armature coils is considered with the aid of Fig. 3. If the fringing flux is not taken into account,

$$V = 3\omega_c \omega_m l_c \quad (\text{m}^3) \quad (3)$$

where l_c is the active length of the conductor on either side of the armature bar, ω_c is the width of the coil section (m) and ω_m is the width of the magnet (m). The equation (2) can be modified to

$$F = 3\omega_c \omega_m l_c J B \quad (\text{N}) \quad (4)$$

$$\text{where } \omega_c \omega_m J = NI \quad (5)$$

which is the m.m.f. of the active part of the armature winding. N is the number of turns of this active part. The force is, therefore,

$$F = 3NB l_c B \quad (\text{N})$$

$$\text{or } F = \frac{3N\phi I}{\omega_m} \quad (\text{N}) \quad (6)$$

$$\text{or } F = 3n\phi I \quad (\text{N}) \quad (7)$$

where n is number of conductors per metre of armature length and ϕ is magnetic flux.

The sensitivity is

$$S_f = \frac{F}{I} = 3n\phi \quad (\text{N/AT}) \quad (8)$$

The constant '3' in Eq. 8 corresponds to the number of permanent magnet pieces surrounding each armature bar.

The electromagnetic power is given by

$$P_e = E_a I = Fv = 3n\phi I v \quad (\text{W}) \quad (9)$$

and the e.m.f. of the coils is

$$E_a = 3n\phi v = S_f v \quad (\text{V})$$

$$= V_t - I r_c - L_c \frac{di}{dt} \quad (\text{V}) \quad (10)$$

where V_t is the terminal voltage, r_c and L_c are the resistance and inductance of the coil.

2.2 Design and Construction

The design was mainly carried out with the knowledge of leakage coefficient, fringing coefficient, magnet length, air gap length, air gap area, reluctance of various magnetic

Fig.3 Section of the armature bar with one permanent magnet

paths. In order to obtain the optimum values of developed force the expression Eq. 7 is made to converge. The operating point of the permanent magnets CRUMAX 315 was initially set at $B_m=0.59T$ and $H_m=-448kA/m$ which coincides with their maximum energy product⁹⁻¹⁰. The operating point was assumed to be the same for all

Table I Measured and numerical values of the air gap flux density

Slider position(mm)	Airgaps flux density in the middle of the permanent magnet face (mT)								
	Bg1			Bg2			Bg3		
	FEM	Meas	diff%	FEM	Meas	diff%	FEM	Meas	diff%
-91.8	561	518	7.6	564	522	7.5	564	523	7.3
-61.2	551	512	7	552	518	6.2	552	518	6.2
-30.6	551	514	6.8	552	518	6.2	552	517	6.3
0.0	551	512	7	552	518	6.1	552	517	6.3
30.6	551	512	7	552	518	6.1	552	517	6.4
61.2	550	512	7	551	518	6	551	516	6.4
91.8	545	511	6.2	548	517	5.6	548	516	5.9

Slider position(mm)	Airgaps flux density in the middle of the permanent magnet face (mT)								
	Bg4			Bg5a			Bg5b		
	FEM	Meas	diff%	FEM	Meas	diff%	FEM	Meas	diff%
-91.8	561	521	7.2	571	537	6	571	564	1.3
-61.2	551	515	6.5	562	540	3.9	562	556	1.1
-30.6	551	516	6.3	563	540	4	563	558	0.8
0.0	551	517	6.1	563	541	3.9	563	559	0.7
30.6	551	516	6.3	563	540	4.1	563	556	1.3
61.2	550	515	6.4	561	539	4	561	558	0.5
91.8	545	515	5.5	518	512	1.1	518	508	1.9

permanent magnets. The nominal armature current was chosen to be 1.5A.

The final design produced a force of 14N, which corresponds to a sensitivity of 9.3N/AT. The travel length of the linear motor was initially chosen to be 214.2mm. Owing to the need to accommodate the slider and fourteen coil sections on each armature bar, it was practically reduced to 184mm (difference between armature bar length and slider length is 214.2-27.6 =186.6mm). Coil sections made from enamelled copper wire of 0.5mm diameter having resistance of 1.52 ohm at 25 °C had length, thickness and nominal active length of 15.3mm, 3.5mm and 24mm respectively. The number of turns and number of layers of each coil section was 159 and 6 respectively.

One of the advantages of using an armature with coil sections, is to have smaller inductance and time constant than in the case of an armature with continuous large windings.

The dimensions of the permanent magnet pieces depend on their second quadrant characteristic, the desired airgap flux density, the dimensions of the coil sections and the air gap. The thickness of the permanent magnets is same as the length of the respective air gaps.

The permanent magnets are placed in the inner part of the slider back iron. Magnets 1 to 4 are glued to their position to avoid being dislocated by the electromagnetic force. Magnet 5 is kept enclosed in a brass piece that also holds the two halves of the slider together.

The width of the permanent magnet pieces has been chosen to cover the length of two coil sections. The total length of two coil sections (30.6mm) is marginally larger than the width of the permanent magnets. This was done on purpose to make a better use of the fringing flux from the permanent magnets without enlarging the coil sections too much.

Fig.4 Distribution of flux density (in tesla) in the linear motor

3. Results and discussion

The linear motor was tested under different conditions. Numerical results produced by the FEM are presented and

compared with the experimental ones wherever possible. A good correlation between them was obtained.

3.1 Static tests

The static tests and simulations were focused on the flux distribution throughout the volume of the prototype and the effect of the current, when it is present, on the flux

Fig. 5 The static force versus position

Table II. Various ratios obtained by measurement and numerical methods.

	Measured	Body	Maxwell	Theoretical
$S_f(N/AT)$	9.54	9.98	9.71	9.33
$\phi(N/cm^3)$	0.965	1.010	0.982	0.944
$\gamma(N/kg \text{ or } m/s^2)$	120.74	126.39	122.95	118.14
$\gamma_c(N/kgA)$	0.084	0.088	0.086	0.083

Table III. Definition and description of the cases analysed.

Case Number	Description
1	Armature current $I=0$
2	Armature current $I=1.5A$, no compensation of armature flux
3	Armature current $I=3A$, no compensation of armature flux
4	Armature current $I=4.5A$, no compensation of armature flux
5	Armature current $I=1.5A$, with compensation of armature flux
6	Armature current $I=3A$, with compensation of armature flux
7	Armature current $I=4.5A$, with compensation of armature flux
8	Double action configuration, armature current $I=1.5A$, with compensation of armature flux
9	Double action configuration, armature current $I=3A$, with compensation of armature flux
10	Double action configuration, armature current $I=4.5A$, with compensation of armature flux

distribution, saturation of the magnetic circuit and force. The results were obtained with the slider of the linear

Fig. 6 Performance of the linear motor in terms of static forces

Table IV. Sensitivity and force-to-mass ratios with slider at $z=0$.

Cases	$S_f(N/AT)$				$\gamma(N/kg \text{ or } m/s^2)$			
	Measured	Body	Maxwell	Theoretical	Measured	Body	Maxwell	Theoretical
2	8.99	9.73	9.42	9.33	37.95	41.04	39.75	39.38
3	8.57	9.37	8.95	9.33	72.29	79.04	75.53	78.76
4	8.32	9.01	8.36	9.33	105.30	114.09	105.85	118.14
5	9.58	9.99	9.87	9.33	40.43	42.17	41.63	39.38
6	9.44	9.99	9.70	9.33	79.66	84.26	81.86	78.76
7	9.54	9.98	9.71	9.33	120.74	126.39	122.95	118.14
8	19.05	19.97	19.40	19.40	80.38	84.25	81.86	78.76
9	19.38	19.97	19.40	19.40	163.50	168.52	163.71	157.52
10	19.16	19.90	19.40	19.40	242.48	251.87	245.57	235.29

Fig. 7 Output power and efficiency of the linear motor

motor placed at seven different positions along the travel length. The experimental results and the predictions obtained by the FEM analysis are closely correlated.

The numerically obtained flux density distribution in the entire volume of linear motor is shown in Fig. 4. In this case the armature current is 4.5A and the armature fringing flux is compensated by energising coils adjacent to the main coils situated opposite to the magnets. The slider is at the middle of the travel length.

Table 1 shows the measured and numerical values of the air gap flux density at a position by the centre of the permanent magnets and 0.5mm away from them towards the armature bar.

The force was computed using two methods: the body force and Maxwell's stress tensor¹¹. The static force curve is presented in Fig. 5 and the ratios are shown in Table 2. In terms of difference with respect to the measured value, the maximum found by body force method was 6.8% and 4% for Maxwell's stress tensor.

Table 3 gives the definitions and descriptions of the cases analysed. These cases cover most of the ways the linear motor can operate.

The performance of the linear motor in terms of static force under different situations represented by cases 2 to 10, Fig.6, can be analysed with the aid of the data, Table 4.

3.2 Dynamic tests

In the dynamic tests, the output power and the efficiency of the linear motor have been evaluated. The test was carried out to estimate the performance of the linear motor in terms of output power and efficiency. For each case, a load was applied. The output power and efficiency of the motor for armature current 4.5A and with compensation of armature flux are shown with variation of the speed in Fig. 7. A load of 3.5 kgf was attached to the slider to obtain the characteristics.

4. Conclusions

The topology of the machine made possible a more efficient use of the armature coils and magnetic circuit. The linear motor proved to be able to produce a high sensitivity, measured values ranging from 9.3N/AT to 19N/AT were obtained; furthermore, its high force-to-mass ratio indicates that its acceleration at constant current can be large.

A good correlation was obtained between the computed values of force using Maxwell's stress tensor method and the measured ones.

In comparison to rotary d.c. motors, which can have efficiencies as high as 90%, the d.c. linear motors in general are less efficient. This is a characteristic of this kind of machine, the airgap is large due to a slotless armature, and, as a result, the airgap flux density is low. However, efficiency is more important when the machine works in a continuous duty cycle. Depending on the duty cycle the linear motor is subjected to, the latter may

perform better than its rotary counterpart.

(Manuscript received Oct. 13, '97, revised April 2, '98)

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