Linear electromagnetic motor with periodic structure of magnetic circuit

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Abstract. The design of the linear electromagnetic motor providing the increase of inductance modulation depth and concentration of magnetic flux in the operating air gaps is considered. The analytical method for calculation of static characteristics of the linear electromagnetic motor with several operating air gaps connected in series into the magnetic circuit is obtained. Calculations are made using the method of the magnetic circuit theory. Based on the Ampere’s circuital law, the expressions of the magnetic flux and traction force are obtained. The comparison of calculating and experimental results is presented.

1. Introduction

The linear electromagnetic motor is the main part of any electromechanical device performing the immediate conversion of the electric power to useful mechanical work [1–8] without any intermediate kinematic links and transmissions. Application of linear electromagnetic motors and machines is considered in [9–16].

Currently, the methods for calculation and design of linear electromagnetic motors are developed and improved [17–25]. Despite the simple design of such motors their application area is limited by relatively low power characteristics.

The power characteristics of the electromagnetic motors can be improved due to the non-uniformity of the magnetic field in the operating air gaps. The linear magnetic system with a non-uniform structure of the magnetic circuit containing the combined armature with two operating air gaps [11, 25] is the example of such motors.

The increase of the magnetic field non-uniformity is successfully implemented in the electromagnetic motors with several operating air gaps connected in series. This effect is provided by the special design of the magnetic system with the periodic non-uniform structure [11].

The electromagnetic motor with the periodic structure of the magnetic circuit is shown in figure 1 [11]. The magnetic circuit of the motor (figure 1) includes the unified magnetic core 1 with the stator and the magnetization winding 2. The magnetic flux is closed through the operating air gaps formed by the magnetic 3, 4 and non-magnetic 5, 6 sections of the moving armature 7 and the stator. Such operation of the electromagnetic motor is similar to the action of the motors connected in series. The number of such motors is equal to the number of ferromagnetic sections of the moving armature or to the number of non-magnetic sections on the stator.
Figure 1. The electromagnetic motor with the periodic structure of the magnetic circuit.

When the armature of the electromagnetic motor is moving, the ratio of the magnetic flux variation and its modulation depth increases. Such design helps to increase the electric power conversion efficiency together with the motor resulting traction force. The maximum force can be increased because of non-uniform design and a more number of the operating gaps in the same volume of the motor. The maximum force is achieved when the face ends of the ferromagnetic sections of the moving armature and the stator are overlaid (figure 1). The armature displacement from the position of the unstable magnetic balance generates the traction force.

With the winding 2 switched on, the moving armature 7 becomes symmetrical relative to the stator position. Here the system magnetic balance is stable, and any external effect causes the counteractive electromagnetic force returning the movable element to the initial position.

2. Calculation of the motor magnetic circuit

The design of the electromagnetic motors requires the calculation of static characteristics with respect to the magnetic field distribution.

The modern software for calculation of the electromagnetic fields is mainly based on the numerical analysis. The most of such software is very precise but expensive. The paper contains the analytical method for electromagnetic fields calculation meeting the requirements of the motor design in practice.

The calculation model of the electromagnetic motor magnetic circuit with periodic non-uniform design is given in figure 2.

It is assumed that the air gaps are large, the magnetic system steel is not saturated and reduction of the magnetization force in individual sections may be ignored. These assumptions simplify the calculation expressions.

When calculations are performed, it is supposed that only the axial component of the magnetic flux in the operating air gaps is taken into account, and the flux radial component is taken into account in the areas occupied by the winding. The magnetic permeability values of the operating air gaps and the armature are different, and the steel magnetic resistance is ignored.
Figure 2. The calculation model of the electromagnetic motor magnetic circuit.

The magnetic circuit along the axis $z$ in figure 1 is divided by $n$ identical areas, each of which is broken down into three sections corresponding to the initial depth of the armature sinking.

For each specified section in figure 2 the closed loops are built. The equations of the balance of the magnetization forces for each section are composed according to the Ampere's circuital law. The coordinate origin has to be placed in the beginning of the corresponding section.

**Calculation of the flux components for the first area.** The flux through the core cross-section with the coordinate $z_{1*}$ relative to the point $O_{1*}:

$$\Phi_{z_{1*}} = \Phi_{A_1} - \int_{O_{1*}} d\Phi_{z_{1*}},$$

(1)

where $\Phi_{A_1}$ is the magnetic flux of the non-operating gap through the standard armature cross-section of the system axis passing through the point $O_{A_1*}$, $d\Phi_{z_{1*}}$ is the elementary leakage flux between the armature and the body at the first section.

The value of the elementary leakage flux is determined from the equation based on the Ampere's circuital law with the loop $O_{A_1*}, z_{A_1*}, b_1, a_1, O_{A_1}$.

With respect to the Ampere's circuital law and assumption that the steel magnetic resistance is equal to zero:

$$\frac{d\Phi_{z_{A_1*}}}{g_1dz_{z_{1*}}} + \Phi_{A_1} R_{A_1} = \frac{l w}{l} z_{1*},$$

(2)

where $R_{A_1} = \Delta/(\mu_0 \pi d_1 l_{A_1})$ is the magnetic resistance of the non-operating gap, $g_1 = \frac{2\pi \mu_0}{\ln(D/d_1)}$ is the specific conductivity of leakage between the armature and the body, $\mu_0 = 4\pi 10^{-7} \text{ H/m}$ is the magnetic permeability of the air, $l w$ is the complete magnetization force of the coil winding.

The solution (2) for the magnetic flux $d\Phi_{z_{A_1*}}$ and substitution of that result into (1) gives:
\[ \Phi_{z_{\lambda_1}} = \Phi_{\Delta l} - \int_{z_{\lambda_1}^*}^{z_{\lambda_1}^*} \left( \frac{Iw}{l} g_1 z_{\lambda_1}^* - \Phi_{\Delta l} R_{\Delta l} \right) dz_{\lambda_1}^*. \]

The integration of the equation above results in:
\[ \Phi_{z_{\lambda_1}} = \Phi_{\Delta l} \left( 1 + R_{\Delta l} g_1 z_{\lambda_1}^* \right) - \frac{Iw}{2l} g_1 z_{\lambda_1}^2. \]

The magnetic flux coming out of the armature face end and entering the first operating air gap of the second section:
\[ \Phi_{z_{\delta l}} = \Phi_{z_{\lambda_1}} \left( \Phi_{z_{\lambda_1}^*} \right) = \Phi_{\Delta l} \left( 1 + R_{\Delta l} g_1 z_{\lambda_1}^* \right) - \frac{Iw}{2l} g_1 \left( \lambda_{\delta l}^* \right)^2. \]

The flux in the non-operating gap is:
\[ \Phi_{\Delta l} = \frac{\Phi_{z_{\delta l}} - \frac{Iw}{2l} g_1 \left( \lambda_{\delta l}^* \right)^2}{1 + R_{\Delta l} g_1 \lambda_{\delta l}^*}. \]

The magnetic flux of the second section in the operating air gap \( \delta_{l} \) normal to axis \( z \) in the point \( z_{\delta l} \) is:
\[ \Phi_{z_{\delta l}} = \Phi_{z_{\delta l}} - \int_{z_{\delta l}}^{z_{\delta l}} d\Phi_{z_{\delta l}}. \]

The value of the elementary leakage flux \( d\Phi_{z_{\delta l}} \) on the second section is found according to the Ampere's circuital law for the loop \( z_{\delta l}, b_2, a_2, O_{\delta l}, z_{\delta l} \) as:
\[ \frac{d\Phi_{z_{\delta l}}}{g_1 dz_{\delta l}} - U_{\delta l} + \int_{O_{\delta l}}^{z_{\delta l}} \frac{\Phi_{z_{\delta l}}}{\mu_0 S_{\delta l}} dz_{\delta l} = \frac{Iw}{l} z_{\delta l}, \]

where \( S_{\delta l} \) is the reduced cross-section of the air gap \( \delta_{l} \), \( U_{\delta l} \) is the difference of the magnetic potentials between the armature and the body at the beginning of the operating air gap \( \delta_{l} \).

The difference of magnetic potentials between the core and the body:
\[ U_{\delta l} = \left( \frac{d\Phi_{z_{\lambda_1}^*}}{g_1 dz_{\lambda_1}^*} \right)_{z_{\lambda_1} = \lambda_{\delta l}^*} = \frac{Iw}{l} \lambda_{\delta l}^* - \Phi_{\Delta l} R_{\Delta l}. \]

The substitution \( d\Phi_{z_{\delta l}} \) from (6) in (5) and the second-order derivation gives:
\[ \frac{d^2\Phi_{z_{\delta l}}}{dz_{\delta l}^2} - \frac{\Phi_{z_{\delta l}}}{\mu_0 S_{\delta l}} g_1 = -\frac{Iw}{l} g_1. \]

The solution of the non-uniform differential equation of the second order (7) has the form:
\[ \Phi_{z_{\delta l}} = \frac{Iw}{l} \mu_0 S_{\delta l} + c_1 e^{p_1 z_{\delta l}} + c_2 e^{-p_1 z_{\delta l}}, \]

where \( p_1 = \sqrt{g_1/\mu_0 S_{\delta l}} \).
The constants of integration $c_1$ and $c_2$ are determined for $z_{01} = 0$ from:

$$\Phi_{z_{01}} = \Phi_{01}; \quad \left( \frac{d\Phi_{z_{01}}}{dz_{01}} \right)_{z_{01}=0} = -U_{01} g_1.$$ 

The difference of magnetic potentials between the intermediate pole and the body at the end of operating air gap $\delta_1$ in the point $O_{\lambda_2}$ is:

$$U_{O_{\lambda_2}} = \left( \frac{d\Phi_{z_{01}}}{g_1 dz_{01}} \right)_{z_{01}=0}.$$ 

The magnetic flux along the third section through the cross-section of the intermediate pole $z_{\kappa_2}$ is:

$$\Phi_{z_{\kappa_2}} = \Phi_{\lambda_2} - \int_{O_{\lambda_2}}^{z_{\kappa_2}} d\Phi_{z_{\lambda_2}}.$$ 

From the equation composed by Ampere's circuital law for the loop $z_{\lambda_2}, b_3, a_3, O_{\lambda_2}, z_{\lambda_2}$, the value the elementary flux $d\Phi_{z_{\lambda_2}}$ is express as:

$$\frac{d\Phi_{z_{\lambda_2}}}{g_2 dz_{\lambda_2}} - U_{O_{\lambda_2}} = \frac{Iw}{l} z_{\lambda_2},$$

$$d\Phi_{z_{\lambda_2}} = (U_{O_{\lambda_2}} g_2 + \frac{Iw}{l} z_{\lambda_2} g_2) dz_{\lambda_2},$$

where $g_2 = \frac{2\pi \mu_0}{\ln(D/d_2)}$ is the specific conductivity of leakage between the section of the intermediate pole and the body.

Substitution of (10) into (9) and integration gives:

$$\Phi_{z_{\lambda_2}} = \Phi_{O_{\lambda_2}} - g_2 U_{O_{\lambda_2}} z_{\lambda_2} - g_2 \frac{Iw}{2l} \left( z_{\lambda_2} \right)^2,$$

where $\Phi_{O_{\lambda_2}} = \left( \Phi_{z_{\lambda_2}} \right)_{z_{01}=0}$ is the flux entering the intermediate pole in the point $O_{\lambda_2}$.

The flux coming out of the intermediate pole into the non-operating gap and passing through the cross-section of the moving armature in the point $O_{\lambda_2}$ is:

$$\Phi_{\lambda_2} = \left( \Phi_{z_{\lambda_2}} \right)_{z_{01}=0} = \Phi_{O_{\lambda_2}} - g_2 U_{O_{\lambda_2}} \lambda_2 - g_2 \frac{Iw}{2l} \left( \lambda_2 \right)^2,$$

The difference of magnetic potentials between the intermediate pole and the body at the end of the pole:

$$U_{\lambda_2} = \left( \frac{d\Phi_{z_{\lambda_2}}}{g_2 dz_{\lambda_2}} \right)_{z_{01}=\delta_1} = U_{O_{\lambda_2}} + \frac{Iw}{l} \lambda_2.$$ 

Calculation of magnetic system flux components in the second area.

The flux through the core cross-section $z_{\lambda_2}$:

$$\Phi_{z_{\lambda_2}} = \Phi_{\Delta_2} \left( 1 + R_{\Delta_2} g_1 z_{\lambda_2} \right) - g_1 U_{\lambda_2} z_{\lambda_2} - g_1 \frac{Iw}{2l} \left( z_{\lambda_2} \right)^2,$$
where \( R_{\Delta 2} = \Delta/\mu_0 \pi d_1 l_{\Delta 2} \), \( l_{\Delta 2} = \lambda_2 - \lambda_1^* \).

The flux entering the second operating gap \( \delta_2 \) is:

\[
\Phi_{\delta 2} = \left( \Phi_{\delta 2} \right)_{z_{\delta 2} = \lambda_2^*} = \Phi_{\Delta 2} \left( 1 + R_{\Delta 2} g_1 \lambda_2^* \right) - g_1 U \lambda_2^* - g_1 \frac{I_w}{2l} \lambda_2^* \right)^2. \tag{12}
\]

The flux in the cross-section of the second operating gap in the point \( z_{\delta 2} \) is:

\[
\Phi_{z_{\delta 2}} = \frac{I_w}{l} \mu_0 S_{\delta 2} + c_3 e^{p_2 z_{\delta 2}} + c_4 e^{-p_2 z_{\delta 2}}. \tag{13}
\]

where \( p_2 = \sqrt{g_1/\mu_0 \lambda_{\delta 2}} \).

The constants of integration \( c_3 \) and \( c_4 \) are determined with respect to \( z_{\delta 2} = 0 \), then:

\[
\Phi_{z_{\delta 2}} = \Phi_{\delta 2}, \quad \left( \frac{d\Phi_{z_{\delta 2}}}{dz_{\delta 2}} \right)_{z_{\delta 2} = 0} = -U_{\delta 2} g_1.
\]

Magnetic flux along the intermediate pole:

\[
\Phi_{\lambda 3} = \Phi_{\lambda 3} = g_2 U_{\lambda 3} z_{\lambda 3} - g_2 \frac{I_w}{2l} z_{\lambda 3},
\]

where \( \Phi_{\lambda 3} = \left( \Phi_{z_{\delta 2}} \right)_{z_{\delta 2} = \lambda_2^*} \), \( U_{\lambda 3} = \left( -\frac{d\Phi_{z_{\delta 2}}}{dz_{\delta 2}} \right)_{z_{\delta 2} = \lambda_2^*} \).

The flux entering the non-operating gap is expressed as:

\[
\Phi_{\lambda 3} = \left( \Phi_{\lambda 3} \right)_{z_{\lambda 3} = \lambda_3} = \Phi_{\lambda 3} = g_2 U_{\lambda 3} \lambda_3 - g_2 \frac{I_w}{2l} \lambda_3. \tag{14}
\]

The difference of magnetic potentials between the intermediate pole and the body at the end of the pole:

\[
U_{\lambda 3} = \left( -\frac{d\Phi_{z_{\delta 2}}}{dz_{\delta 2}} \right)_{z_{\delta 2} = \lambda_2^*} = U_{\lambda 3} + \frac{I_w}{l} \lambda_3.
\]

**Calculation of the magnetic circuit flux components for n-area.**

The similar calculations for the following sections of the magnetic circuit produce the expressions for determination of the magnetic fluxes along the sections for the n-area.

In the first section:

\[
\Phi_{z_{\lambda n}} = \Phi_{\lambda n} \left( 1 + R_{\lambda n} g_1 z_{\lambda n} \right) - g_1 U_{\lambda n} z_{\lambda n} - g_1 \frac{I_w}{2l} \lambda_n \right)^2, \tag{15}
\]

where \( R_{\lambda n} = \Delta/\mu_0 \pi d_1 l_{\lambda n} \), \( l_{\lambda n} = \lambda_n - \lambda_{n-1} \).
\[ \Phi_{\delta n} = \left( \Phi_{z_{n}^{*}} \right)_{z_{n}^{*} = z_{n}} = \Phi_{\Delta n} \left( 1 + R_{\Delta n} g_{1} \lambda_{n}^{*} \right) - g_{1} U_{\lambda n} \lambda_{n}^{*} - \frac{I_{w}}{2} \lambda_{n}^{*} \lambda_{n}^{*}, \]  
\[(15)\]

where \( U_{\lambda n} = \left( -\frac{d\Phi_{z_{n}^{*}}}{g_{2} d z_{n}} \right) \), \( z_{n} = \lambda_{n} \),

\[ U_{\lambda n} = \left( -\frac{d\Phi_{z_{(n-1)}^{*}}}{g_{1} d z_{(n-1)}^{*}} \right) \]  
\[ z_{(n-1)}^{*} = z_{(n-1)} \]  
\[ \delta_{(n-1)} = \delta_{(n-1)} \]  

In the second section:

\[ \Phi_{z_{0n}} = \frac{I_{w}}{l} \mu_{0} S_{\delta} + c_{(2n-1)} e^{p_{n} z_{0n}} + c_{2n} e^{-p_{n} z_{0n}}, \]

\[(16)\]

where \( p_{n} = \sqrt{g_{1}/\mu_{0} S_{\delta}} \). If \( \delta_{1} = \delta_{2} = \ldots = \delta_{n} \), then \( p_{1} = p_{2} = \ldots = p_{n} \).

The condition for determination of the constants of integration \( c_{(2n-1)} \) and \( c_{2n} \) if \( z_{0n} = 0 \) is:

\[ \Phi_{z_{0n}} = \Phi_{\delta n}, \quad \left( \frac{d\Phi_{z_{0n}}}{dz_{0n}} \right)_{z_{0n} = 0} = -U_{\delta n} g_{1}. \]

At the third section:

\[ \Phi_{\lambda_{(n+1)}^{*}} = \Phi_{\lambda_{n}^{*}} - g_{2} U_{\lambda_{(n+1)}^{*}} z_{\lambda_{(n+1)}^{*}} - \frac{I_{w}}{l} \lambda_{n}^{*} \lambda_{n}^{*}, \]

where \( \Phi_{\lambda_{n}^{*}} = \left( \Phi_{z_{\lambda_{n}^{*}}^{*}} \right)_{z_{\lambda_{n}^{*}}^{*} = \lambda_{n}^{*}}, \quad U_{\lambda_{n}^{*}} = \left( \frac{d\Phi_{z_{\lambda_{n}^{*}}^{*}}}{d z_{\lambda_{n}^{*}}^{*}} \right)_{z_{\lambda_{n}^{*}}^{*} = \lambda_{n}^{*}} \)

\[ \Phi_{\lambda_{(n+1)}^{*}} = \left( \Phi_{z_{\lambda_{(n+1)}^{*}}^{*}} \right)_{z_{\lambda_{(n+1)}^{*}}^{*} = \lambda_{(n+1)}^{*}} = \Phi_{\lambda_{n}^{*}} - g_{2} U_{\lambda_{n}^{*}} \lambda_{3} - g_{2} \frac{I_{w}}{l} \lambda_{3}^{2}. \]

\[(17)\]

Further the expression of the magnetic flux \( \Phi_{\delta 1} \) in the operating air gap \( \delta_{1} \) is determined. With respect to the equation of the system magnetization force balance and the assumption that the steel magnetic resistance is equal to zero, the following equation is obtained:

\[ \sum_{n=1}^{m} \frac{1}{\mu_{0} S_{\delta n} O_{n}} \int \Phi_{z_{\lambda n}^{*}} d z_{\lambda_{n}} + \sum_{n=1}^{m} \Phi_{\Delta n} R_{\Delta n} = I_{w}. \]

\[(18)\]

Substitution of (4), (8), (13), (14), (16), (17) to (18) and integration after a number of transformations, the expression for the flux \( \Phi_{\delta 1} \) is determined as the function of the magnetization force and geometrical dimensions.

The traction force acting in the \( n \)-th operating gap with account of the fact that the magnetic system is practically linear:

\[ F_{n} = \frac{\Phi_{\delta_{n}}^{2}}{2 \mu_{0} S_{\delta n}}. \]

\[(19)\]
The resulting traction force of the whole system is determined as the total of the forces in each independent operating air gap of the system \( F = \sum_{n=1}^{m} F_n \). The flux \( \Phi_{\delta_1} \) is determined by (18), the fluxes \( \Phi_{\delta_2} \) and \( \Phi_{\delta_n} \) are found from (12) and (15).

The reduced cross-section of the operating air gap is determined as \( S_{\delta_n} = \frac{G_{\delta_n} \delta_n}{\mu_0} \), where \( G_{\delta_n} \) is the complete conductivity of the operating air gap.

3. Main results of research

The results of the calculation of the magnetic flux distribution along the coil of the electromagnetic motor with two operating air gaps are illustrated in figure 3.

The motor has the following dimensions: \( D = 80 \) mm, \( d_1 = 30 \) mm, \( d_2 = 46 \) mm, \( l = 70 \) mm, \( \lambda_2 = 31 \) mm, the parasitic gap \( \Delta = 2 \) mm. The number of the magnetizing coil turns is \( w = 560 \). The winding is current \( I = 10A \).

The calculations according to the proposed method were made in MathCAD.

![Figure 3. The magnetic flux distribution plot.](image)

The calculated and experimental data for the electromagnetic motor with two operating air gaps in the magnetic circuit are given in table 1.

The calculation error (table 1) is:

\[
\Delta\% = \frac{\sum F_{\delta_{\text{cal}}} - F_{\delta_{\text{exp}}}}{F_{\delta_{\text{exp}}}} \times 100\% ,
\]

where \( F_{\delta_{\text{cal}}} \) is the calculated value of the traction force; \( F_{\delta_{\text{exp}}} \) is the experimental value of the traction force.

| \( \delta \) | \( F_{\delta_{\text{cal}}} \) | \( F_{\delta_{2\text{cal}}} \) | \( \sum F_{\delta_{\text{cal}}} \) | \( F_{\delta_{\text{exp}}} \) | Error, \( \Delta \) |
|---|---|---|---|---|---|
| mm | N | N | N | N | % |
| 2 | 245 | 180 | 425 | 352 | 17.6 |
| 3 | 159 | 125 | 284 | 321 | 11.25 |
| 4 | 114 | 96 | 210 | 239 | 12.1 |
| 5 | 87 | 78 | 165 | 190 | 13.6 |
4. Conclusion
Comparison of the calculated and experimental data for electromagnetic motors with the variable number of the operating air gaps demonstrates the accuracy of the obtained expressions sufficient for engineering calculations. When the number of the operating gaps is increased, the accuracy of calculation is improved. When the number of the operating gaps is reduced, the obtained formulas describe only the initial part of the traction characteristic with sufficient accuracy, which is determined by the reduction of the magnetic potential in the steel sections of the magnetic core. The error of the traction force is no more than 20%.

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