DOI: 10.25515/PMI.2018.1.62

UDC 621.3.049.77

DEVELOPMENT OF THE SYSTEM FOR AIR GAP ADJUSTMENT AND SKIP PROTECTION OF ELECTROMAGNETIC LIFTING UNIT

Bakhyt A. ZHAUTIKOV, Altyn A. AIKEYEVA
Karaganda State Industrial University, Temirtau, Republic of Kazakhstan

The efficiency of the electromagnetic lifting system is ensured by the well-coordinated work of all its parts and elements, namely those providing the strictly vertical movement of the skip. The deviation of the skip movement from the vertical axis can lead to a stop and damage of both the skip and the unit. Therefore, the air gap adjustment and skip protection system of the electromagnetic lifting system, which includes determining the size of the air gap between the electromagnet of the skip and the electromagnet of the aligning device, and the development of a stabilization system to ensure a constant air gap and regulate the current in the electromagnet winding, provide both a strictly vertical movement skip, and its protection.

The article is devoted to the theoretical determination of the air gap between the electromagnets of the aligning device and the skip using the Biot – Savar – Laplace law.

***Key words*:** electromagnet, magnetic levitation, electromagnetic forces, unit

***How to cite this article*:** Zhautikov B.A., Aikeyeva A.A. Development of the System for Air Gap Adjustment and Skip Protection of Electromagnetic Lifting Unit. Zapiski Gornogo instituta. 2018. Vol. 229, p. 62-69. DOI: 10.25515/PMI.2018.1.62

The electromagnetic lifting system consists of a lifting vessel (skip), electric magnets (or permanent magnets) and aligning conductors. By the force of electromagnetic interaction, the vessel is set in motion. Since there is a gap between the skip and the aligning devices, friction is eliminated, and the only braking force is the aerodynamic drag. Previously the magnetic levitation for the transportation of rock mass has never been used anywhere in the world and the creation of this unit entails the introduction of a new innovative technology for transporting rock mass in the mining industry and construction.

Unlike the existing lifting machines, the unit has a greater load capacity with less consumption of electricity and other energy resources, so this transportation technology can be considered as energy-saving.

Electric magnets with high lifting force are used in engineering for various purposes. For example, an electromagnetic lifting crane is used in metallurgical and metal processing plants, in ports for carrying iron scrap and finished products. Metal processing plants use machines with magnetic tables, on which the processed metal product is fixed by the force of strong electromagnets [4, 7].

Let us consider the electric magnet with an axial direction of magnetization (Fig.1), the magnetizing current I flows along the winding of this magnet.

The magnetic moment of the electric magnet P can be calculated using the following formula

$$P = jhS,$$

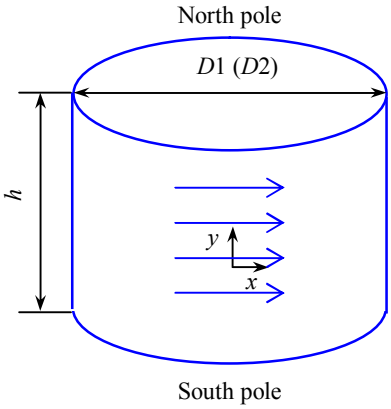


Fig.1. Electromagnet with axial direction of magnetization

where $j = I/h$ – linear density of the magnetizing current, which can be expressed by the approximate formula

$$j = B_r / m_0,$$

B_r – residual magnetic induction; $m_0 = 4 \cdot 10^{-7}$ H/m – magnetic constant.

The magnitude and direction of the magnetic induction vector $\overrightarrow{dB}$ at an arbitrary point of the magnetic field, created by the element of the conductor $\overrightarrow{dl}$ with current I, can be found using the Biot – Savart – Laplace law [18]:

$$\overrightarrow{dB} = \frac{\mu\mu_0}{4\pi}\frac{I}{r^3}\left[\overrightarrow{dl}\,\vec{r}\right],$$

DOI: 10.25515/PMI.2018.1.62

where $\vec{dl}$ is the modulus of a vector equal to the length of dl element of the conductor and matching the direction of current flow; $\vec{r}$ is the radius vector drawn from the conductor element $\vec{dl}$ to the considered point of the field.

The modulus of vector $\vec{dB}$ is defined by the formula

$$B = \frac{\mu\mu_0}{4\pi}\frac{Idl}{r^2}\sin a,$$

where α – angle between vectors $\vec{dl}$ and $\vec{r}$.

For the magnetic field, the principle of superposition is valid: the vector of magnetic induction of the resultant field created by several currents or moving charges is equal to the vector sum of the magnetic inductions of the fields created by each current or moving charge separately [14]:

$$\vec{B} = \sum_{i=1}^{n}\vec{B_i}.$$

The total magnetic field created by this conductor with current at point A, can be calculated as the vector sum of the fields created by all individual elements of $\vec{dl}$ at the same point. This summation in the limit becomes the integration action:

$$B = \int dB = \frac{\mu\mu_0 I}{4\pi}\int \frac{\sin(\vec{dl}\wedge\vec{r})dl}{r^2}.$$

Let us define the expression for the magnetic induction in the center of one winding turn with the coil current (Fig.2). The distance r from any element of $\vec{dl}$ to the center O is the same, that is equal to the winding turn radius R. All elements are perpendicular to radius vector that is why $\sin(\vec{dl}\wedge\vec{r}) = 1$. Consequently,

$$B = \int dB = \frac{\mu_0\mu I}{4\pi R^2}\int_0^{2\pi R} dl = \frac{\mu_0\mu I}{4\pi R^2}2\pi R = \frac{\mu_0\mu I}{2R}.$$

If the medium around the conductor is nonmagnetic, μ = 1. Then

$$B = \frac{\mu_0 I}{2R}.$$

If there are N winding turns in the coil of the electromagnet, then

$$B = \frac{\mu_{0\mu} IN}{2R}.$$

Now we define the induction of the magnetic field of the winding turn with the current at an arbitrary point A on its axis. The axis of the turn z is a straight line, which passes through the center of the turn and is perpendicular to the plane of the cross section [16].

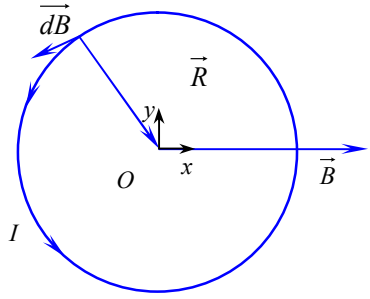


Fig.2. Induction of the magnetic field in the center of the winding turn of the electromagnet coil with the axial direction of magnetization

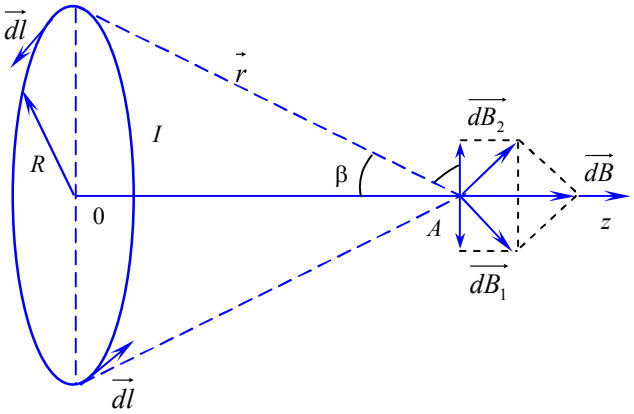


Fig.3. Induction of the magnetic field on the axis of the circular

DOI: 10.25515/PMI.2018.1.62

Figure 3 shows circular turn of radius R, which plane is perpendicular to the plane of the drawing. The element distance $\vec{dl}$ to point A will be denoted as $\vec{r}$. The angle between $\vec{dl}$ and $\vec{r}$ is equal to $\pi/2$ (as the angle between cone generator and element of the circle of its base).

At point A on axis z the vectors of induction of fields created by different small elements of a winding turn with current, do not coincide in direction. The magnetic field of a winding turn with current has rotational symmetry, that is why vectors $\overrightarrow{dB_1}$ and $\overrightarrow{dB_2}$ for fields of two diametrically opposite elements of winding turn dl_1 and dl_2, having the same length ($dl_1 = dl_2 = dl$), are equal in absolute value

$$\left|\overrightarrow{dB_1}\right| = \left|\overrightarrow{dB_2}\right| = \frac{\mu_0 Idl}{4\pi r^2}.$$

The resulting vector $\left|\overrightarrow{dB}\right| = \left|\overrightarrow{dB_1}\right| + \left|\overrightarrow{dB_2}\right|$ in point A is directed along axis z and is equal in absolute value to $\left|\overrightarrow{dB}\right| = \left|\overrightarrow{dB_1}\right| \sin\beta$, where $\sin\beta = R/r$.

Substituting the value $\sin\beta$, we have

$$dB = \frac{\mu_0 IRdl}{4\pi r^3}.$$

The induction of the magnetic field created by the whole winding turn has the same direction, and its modulus is [12]

$$B = \int_0^{2\pi R} \frac{\mu_0 IRdl}{4\pi r^3} = \frac{\mu_0 IR}{4\pi r^3} \int_0^{2\pi R} dl = \frac{\mu_0 IR^2}{2r^3}.$$

From Figure 3 it is seen that $r^2 = R^2 + z^2$, where z is a distance from the center of section 0 to point A. Then

$$r^3 = (R^2 + z^2)\sqrt{R^2 + z^2} = R^3\left[1 + \left(\frac{z}{R}\right)^2\right]^{\frac{3}{2}}.$$

Substituting this value from the previous formula, we can calculate the induction of the field along the axis of the winding turn with current:

$$B = \frac{\mu_0 IR^2}{2R^3\left[1 + \left(\frac{z}{R}\right)^2\right]^{\frac{3}{2}}} = \frac{\mu_0 I}{2R\left[1 + \left(\frac{z}{R}\right)^2\right]^{\frac{3}{2}}}.$$

If the number of winding turns in the electromagnet coil is N, then the resulting expression must be multiplied by N.

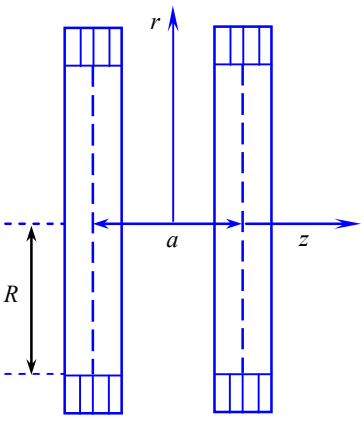


Fig.4. Interaction of electromagnets

To theoretically calculate the resultant interaction field of electromagnets, we place the origin of coordinates at a point lying on a line connecting their centers at the same distance and use the formula for calculating the magnetic induction $\vec{B}$ for one electromagnet [13].

It is obvious that the induction $\vec{B}$ of the magnetic field at a point on the axis of two identical electromagnets (Fig.4) at a distance A_1 and A_2 from them is equal to

$$B(x, r=0) = \frac{\mu\mu_0 NI}{2R}\left[\frac{1}{\left(1 - A_1^2\right)^{\frac{3}{2}}} + \frac{1}{\left(1 + A_2^2\right)^{\frac{3}{2}}}\right],$$

where $A_1 = \frac{z + \frac{a}{2}}{R}$, $A_2 = \frac{z - \frac{a}{2}}{R}$; a – distance between electric magnets.

DOI: 10.25515/PMI.2018.1.62

With $z = 0$ and $a < R$ the induction of magnetic field has maximum value, if $a > R$, then it has minimum value. If $a = R$, then the field is almost homogeneous within the range $-R < z < +R$. Then

$$B = \int_{-R}^{R} \frac{\mu\mu_0 NI}{2R} \left[\frac{1}{\left(1 - \left(\frac{z + \frac{a}{2}}{R}\right)^2\right)^{\frac{3}{2}}} + \frac{1}{\left(1 + \left(\frac{z - \frac{a}{2}}{R}\right)^2\right)^{\frac{3}{2}}} \right] dz.$$

For the calculation of the system «electric magnet of the skip – electric magnet of aligning device» of the electric magnetic lifting unit it is recommended to use the system of cylindrical coordinates. The center of the coordinate system in this case is better to place at the axis of electric magnetic system in the middle between electric magnets, that is at the distance $s/2$ from upper base of the electric magnet 1, and from the lower one (Fig.5) [8].

Since the magnetic system consists of two electric magnets, in accordance with the superposition principle its magnetic field is equal to the sum of the magnetic fields of electric magnets. Let us introduce the following notations. The magnetic induction of electric magnet 1 has radial $B1_x(X, 0, Z)$ and axial $B1_z(X, 0, Z)$ components (it was calculated according to the Biot – Savart – Laplace law in relation to the center of electric magnet 1 with residual induction B_r1). The magnetic induction of electric magnet 2 has radial $B2_x(X, 0, Z)$ and axial $B2_z(X, 0, Z)$ components (it was calculated according to the Biot – Savart – Laplace law in relation to the center of electric magnet 2 with residual induction B_r2). The magnetic induction $B12(X, 0, Z)$ of the electric magnetic system has radial $B12_x(X, 0, Z)$ and axial $B12_z(X, 0, Z)$ components calculated in relation to the center of the base taking into account that the electric magnets are placed at a distance s from each other [10, 11, 15]:

$$B12_x(X, 0, Z) = B1_x\left(X - \frac{h_2}{2} - \frac{s}{2}, 0, Z\right) + B2_x\left(X + \frac{h_2}{2} + \frac{s}{2}, 0, Z\right);$$

$$B12_z(X, 0, Z) = B1_z\left(X - \frac{h_2}{2} - \frac{s}{2}, 0, Z\right) + B2_z\left(X + \frac{h_1}{2} + \frac{s}{2}, 0, Z\right).$$

The modulus of magnetic induction of the systems $B12(X, 0, Z)$ is

$$B12(X, 0, Z) = \sqrt{[B12_x(X, 0, Z)]^2 + [B12_z(X, 0, Z)]^2}.$$

To calculate the interacting force (attraction or repulsion) of magnets we indicate that magnetic field of the electric magnet 1 with radial $B1_x(X, 0, Z)$ and axial $B1_z(X, 0, Z)$ components of the magnetic induction (it was calculated according to the Biot – Savart – Laplace law in relation to the center of electric magnet 1) is acting on the other same magnet with linear density of the current $j_2 = \pm\frac{B_r 2}{m_0}$ and creates the Ampere force (the Ampere force is a force acting from the magnetic field on the conductor with current). The Ampere force dF, acting on the small element dl of the conductor length with current I, equals to

$$\overrightarrow{dF} = I[\overrightarrow{dl} \wedge \overrightarrow{B}],$$

DOI: 10.25515/PMI.2018.1.62

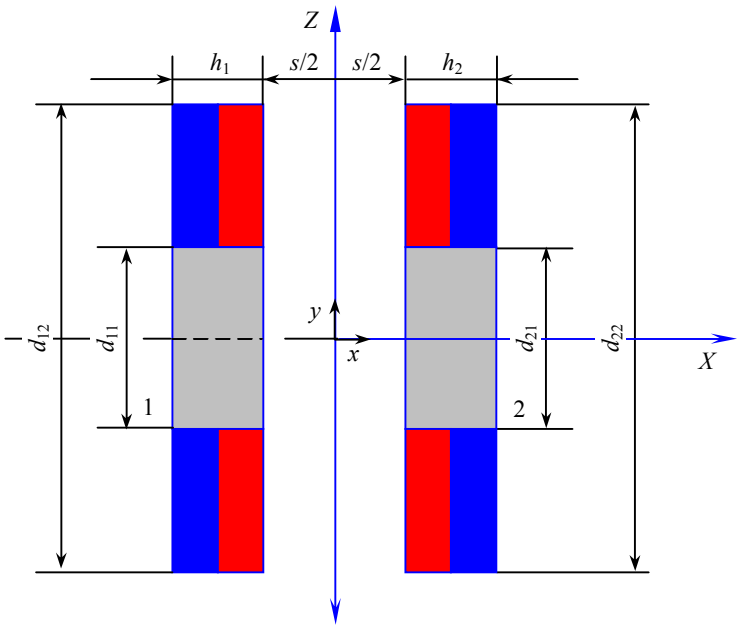


Fig.5. Scheme of a magnetic system of two electromagnets (the center of coordinates is on the axis of the system in the middle between the electromagnets); X is the radial coordinate; Z – axial coordinate

where $\vec{dl}$ – vector numerically equal to the length of dl conductor element and having the same direction as the vector $\vec{j}$ of current density of this conductor element [9].

If vectors $\vec{dl}$ and $\vec{B}$ are mutually perpendicular, then the direction of the force $\vec{dF}$ can be found according to the Fleming's Left Hand Rule: if the palm of the left hand is placed so that the vector of a magnetic induction enters the palm, and four extended fingers point to the direction of the electric current flow, then the extended thumb points in the direction of the force exerted from the field upon the conductor [19].

The interacting force arising due to the axial component of the magnetic induction of the magnet field, has only radial component. Its impact on the solenoid is reduced to its radial contraction (extension). Thus, the desired force is determined only be radial component of $B1_x$ induction of magnetic field of electric magnet 1. The radial component of the magnetic field induction of the electromagnet 1 and and the vector of linear density of current $\vec{j}_2$ in electric magnet 2 are mutually perpendicular.

The linear density of current in electric magnet 2 for the internal diameter $D21$ of electric magnet is

$$j_2\left(X, 0, \frac{D21}{2}\right) = -\frac{B_r 2}{m_0}.$$

Then for the elementary Ampere force is

$$d^2F = \left[j_2\left(X, 0, \frac{D22}{2}\right) B1_x\left(X, 0, \frac{D22}{2}\right)\frac{D22}{2} dfdX + j_2\left(X, 0, \frac{D21}{2}\right) B1_x\left(X, 0, \frac{D21}{2}\right)\frac{D21}{2} dfdX \right],$$

where $\frac{D22}{2}df$ and $\frac{D21}{2}df$ are elements of the conductor length of electromagnet winding in the cylindrical coordinate system [5].

Taking into account the axial symmetry of the system

$$\int_0^{2\pi} df = 2\pi;$$

$$dF = \frac{\pi B_r 2}{\mu_0}\left[D22B1_x\left(X, 0, \frac{D22}{2}\right) + D21B1_x\left(X, 0, \frac{D21}{2}\right) dX \right].$$

Taking into account the position of the coordinate system the limits of integration along Z will be from $\frac{s}{2}$ to $\frac{s}{2} + h_2$, and the radial component of magnetic induction of electric magnet 1 $B1_x$

DOI: 10.25515/PMI.2018.1.62

should be calculated at points $\left(X+\frac{h_1}{2}+\frac{s}{2},0,\frac{D22}{2}\right)$ and $\left(X+\frac{h_1}{2}+\frac{s}{2},0,\frac{D21}{2}\right)$, that is in relation to the center of the coordinates of the magnet base

$$F=\frac{\pi B_r 2}{\mu_0}\int_{\frac{s}{2}}^{\frac{s}{2}+h_2}\left[D22B1_x\left(X+\frac{h_1}{2}+\frac{s}{2},0,\frac{D22}{2}\right)+D21B1_x\left(X+\frac{h_1}{2}+\frac{s}{2},0,\frac{D21}{2}\right)dX\right].$$

Substituting the expressed values of magnetic induction, we obtain an expression for determining the interacting force of electromagnets [1]:

$$F=\frac{\pi B_r 2}{\mu_0}\int_{\frac{s}{2}}^{\frac{s}{2}+h_2} D22\frac{\mu\mu_0 NI}{D22}\left[\frac{1}{1-\frac{(2x+s+h)^2}{D22^2}}+\frac{1}{1+\frac{(2x-s-h)^2}{D22^2}}\right]+D21\frac{\mu\mu_0 NI}{D21}\times$$

$$\times\left[\frac{1}{1-\frac{(2x+s+h)^2}{D21^2}}+\frac{1}{1+\frac{(2x-s-h)^2}{D21^2}}\right]dX.$$

Having simplified the obtained values, we get the resulting expression:

$$F=\frac{\pi B_r 2\mu IN}{1}\int_{\frac{s}{2}}^{\frac{s}{2}+h_2}\left[\frac{1}{1-\frac{(2x+s+h)^2}{D22^2}}+\frac{1}{1+\frac{(2x-s-h)^2}{D22^2}}\right]+\left[\frac{1}{1-\frac{(2x+s+h)^2}{D21^2}}+\frac{1}{1+\frac{(2x-s-h)^2}{D21^2}}\right]dX.$$

According to Newton's third law, the lifting of the skip of the electromagnetic lifting system will be carried out under the condition that the interacting force between the electromagnets and the force of gravity of the skip is equal. Then the maximum carrying capacity is

$$m_s=\frac{\pi B_r 2\mu IN}{g}\int_{\frac{s}{2}}^{\frac{s}{2}+h_2}\left[\frac{1}{1-\frac{(2x+s+h)^2}{D22^2}}+\frac{1}{1+\frac{(2x-s-h)^2}{D22^2}}\right]+\left[\frac{1}{1-\frac{(2x+s+h)^2}{D21^2}}+\frac{1}{1+\frac{(2x-s-h)^2}{D21^2}}\right]dX,$$

where m_s – weight of the skip; g – free fall acceleration.

The calculations were carried out to determine the interacting force of two identical electromagnets with an amount of winding turns N equal to 500, 1000, 1500 and 2000, and with a core diameter of 0.016 m, spaced from 0 to 3 cm apart. Each solenoid was supplied with a constant voltage of 30 V. The core material was steel, the winding material was copper wire 0.5 mm in diameter. The width of each electromagnet is 0.035 m.

The interacting force calculations for each pair of tested electromagnets were carried out in the MathCad 15 program. Based on the calculation results, plots of the interacting force of the two electromagnets versus the air gap were plotted. The graph shows curves with extrema of the continuous function $F_i(s)$, which have local character. This means that the function compiled for each electromagnet has one largest value of the function as compared to nearby values (Fig.6). The point at which the extremum of the interacting force function is determined defines the size of the air gap for the investigated electromagnet [1-3, 6, 8].

DOI: *10.25515/PMI.2018.1.62*

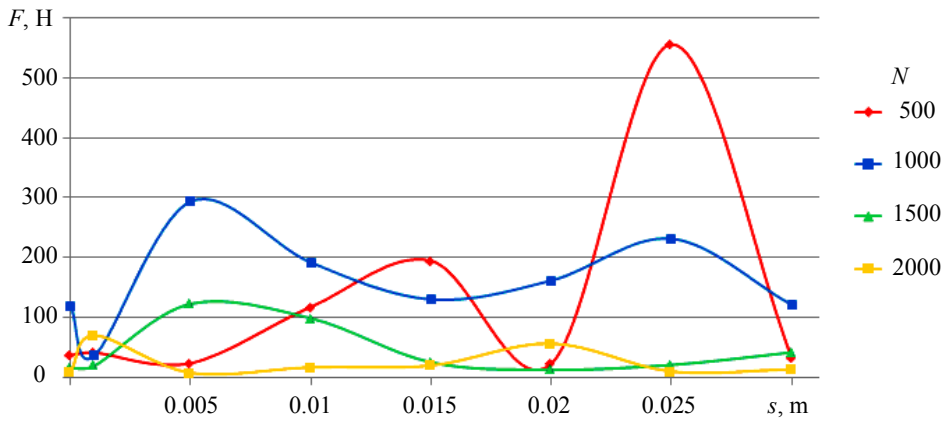


Fig.6. Calculation results of the interacting force of electromagnets

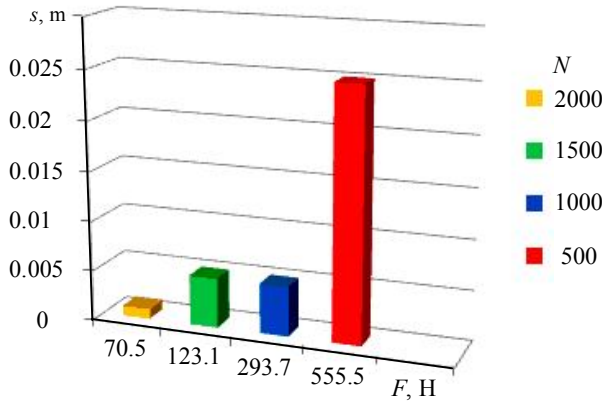


Fig.7. Determination of the gap for electromagnets with different number of turns *N*

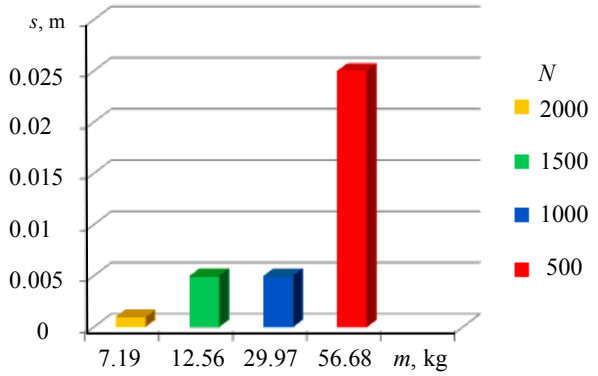


Fig.8. The dependence of the gap on the possible carrying capacity

The gaps for electromagnets with the number of winding turns 500, 1000, 1500 and 2000 are set in accordance with Fig.7.

Thus, based on the results of the studies, the size of the air gap of the investigated electromagnets was determined, as well as the maximum load capacity of the electromagnets for certain gaps. The diagram of air gap size dependence on the possible load capacity is shown in Fig.8.

Conclusions

1. A system for regulating the air gap and protecting the skip of the electromagnetic lifting system has been developed. According to the Biot – Savart – Laplace law, an expression is obtained for determining the magnetic induction for the interaction of two identical electric magnets, the vector analysis and calculation of the resultant field were carried out.

2. Using the method of cylindrical coordinates, an expression is obtained for determining the interacting force between the electromagnet of the skip and the electromagnet of the aligning device.

3. The size of the air gap for electromagnets with the number of winding turns 500, 1000, 1500, 2000, depending on the interacting force of electromagnets is determined.

4. The choice of the most effective electromagnet with the number of winding turns 1500 is substantiated and the optimal air gap size of 5 mm for this magnet is determined.

REFERENCES

1. Veits V.L. Dynamics of machine equipment. Moscow: Mashinostroenie, 1969, p. 285 (in Russian).

2. Veits V.L., Kochura A.E., Martynenko A.M. Dynamic calculations of machine drives. Leningrad: Mashinostroenie, 1971, p. 182 (in Russian).

3. Veits V.L., Tsarev G.V. Dynamics and modeling of electromechanical drives. Saransk: Izd-vo Mordovskogo gosudarstvennogo universiteta, 1992, p.291 (in Russian).

4. Zhautikov B.A., Aikeeva A.A., Zhautikov F.B., Mukhtarova P.A. Innovative patent for invention № 27177 MU PK. Elektromagnitnaya pod"emnaya ustanovka (varianty). Zareg. 25.06.2013 (in Kazakhstan).

5. Degtyarev Yu.I. Research of operations. Moscow: Vysshaya shkola, 1986, p. 320 (in Russian).

6. Mark D.A., Mak-Gouen K. Methodology of structural analysis and design. Moscow: Metatekhnologiya, 1993, p. 240 (in Russian).

7. Nikolaev Yu.A., Zhautikov B.A., Aikeeva A.A. Development of a technique for determining the permissible wall thickness of a skip. Trudy Mezhdunar. nauchn. konf. «Nauka i obrazovanie – vedushchii faktor strategii «Kazakhstan-2030». KarGTU, 2006, p. 314-317 (in Russian).

8. Pugachev B.C., Sinitsyn I.N. Theory of stochastic systems. Moscow: Logos, 2000, p. 161 (in Russian).

9. Svecharnik D.V. Linear electric drive. Moscow: Energiya, 1979, p. 152 (in Russian).

10. Appunn R., Hameyer K. Modern high speed elevator systems for skyscrapers. Maglev-2014. Rio de Janeiro, Brazil. 2014, p.24.

11. Appunn R., Schmulling B., Hameyer K. Electromagnetic guiding of vertical transportation vehicles: experimental evaluation. *IEEE Trans ind Electron*. 2010. N 57(1), p. 335-343.

12. Kim C.H., Lim J., Ahn C., Park J., Park D.Y. Control design of passive magnetic levitation tray. International conference on electrical machines and systems. Busan, Korea. 2013, p. 79

13. Park J.W., Kim C.H., Park D.Y., Ahn C. Controller design with high fidelity model for a passive maglev tray system. *Int. J. Precis. Eng. Manuf*. 2014. N 15(8), p. 1521-1528.

14. Kim K.J., Han H.S., Kim C.H., Yang S.J. Dynamic analysis of a Maglev conveyor using an EM-PM hybrid magnet. *J Electr. Eng. Technol*. 2013. N 8(6), p. 1571-1578.

15. Kim B.S., Park J.K., Kim D.I., Kim S.M., Choi H.G. Integrated dynamic simulation of a magnetic bearing stage compatible for particle free environment. Proceedings of the 14theuspen international conference. Dubrovnik, Croatia. 2014, p. 98

16. Kim C.H., Lee J.M., Han H.S., Lee C.W. Development of a maglev LCD glass conveyor. Maglev-2011. Daejeon, Korea. 2011, p. 36.

17. Li S.E., Park J.W., Ahn C. Design and control of a passive magnetic levitation carrier system. *Int. J. Precis. Eng. Manuf*. 2015. N 16(4). P. 693-700.

18. Ohsaki H. Japanese superconducting maglev-development and commercial serviceplan. Maglev-2014. Rio de Janeiro, Brazil. 2014, p. 21.

19. Zhao C.F., Zhai W.M. Maglev vehicle/guideway vertical random response and ride quality. *Veh. Syst. Dyn*. 2002. N 38(3), p. 185-210.

***Authors*: Bakhyt A. Zhautikov,** *Doctor of Engineering Sciences*, *Professor*, *info@kgiu.kz* (*Karaganda State Industrial University, Temirtau, Republic of Kazakhstan*), **Altyn A. Aikeyeva,** *Candidate of Engineering Sciences*, *Associate Professor*, *aikeeva@mail.ru* (*Karaganda State Industrial University, Temirtau, Republic of Kazakhstan*).

The paper was accepted for publication on 3 May, 2017.