Design, Analysis and Experiment Study of the Permanent Maglev Roller used in Belt Conveyor

Li Zhang[a,b], Huachun Wu[a,b] ,Peng Li[a,b], Yefa Hu[a,b], Chuanyang Xu[c], Lei Wang[c], Ziyang Zhang[c]

[a] School of Mechanical and Electronic Engineering, Wuhan University of Technology, Wuhan, Hubei 430070, China. Email: {zliss0520, whc, lp, huyefa }@whut.edu.cn
[b] Hubei Provincial Engineering Technology Research Center for Magnetic Suspension, Wuhan, Hubei 430070, China
[c] Shandong Haihui Environmental Protection Equipment Co., Ltd.， Shandong, juxian 276526, China
Email:{18606338826@163.com，haihuiwanglei@163.com，1132556777@qq.com}

***Abstract*—The transport energy consumption of the belt conveyor can be reduced by using the maglev roller instead of the mechanical roller. In this research, the structure of permanent magnetic roller is studied. The mathematical model of the permanent magnetic bearing used in the roller is established by using the equivalent magnetic charge method (EMCM). Then the bearing characteristics of the permanent magnetic bearing are analyzed by using the finite element method (FEM). The structure parameters of the optimized magnetic levitation roller are obtained. Through the experiment study, the rotating resistance of the maglev roller can be reduced to 1.4N, which is far less than the design requirements of the mechanical rollers. And the radial round jump of the maglev roller is at 0.18-0.25mm, less than the radial round jump of the high quality mechanical roller. The analysis of the theory is verified.**

I. I. INTRODUCTION

As a kind of common bulk conveying equipment, compared with other transportation equipment, belt conveyor is widely used in the industries of coal, metallurgy, mining, electric power, and so on. Belt conveyor mainly consists of conveyor belt, driving device, roller, frame and tensioning device. Among them, as an important component of the belt conveyor, rollers have many kinds and large quantities, which can support conveyor belts and materials. The cost of the roller takes up 35% of the total cost of the belt conveyor, but it produces more than 70% of the energy consumption [1]. Therefore, the quality of the roller is especially important.

The energy consumption of the ordinary mechanical rollers mainly comes from the friction and wear of the mechanical bearings, which will increase the rotation resistance of the roller, thus increasing the power consumption and limiting the transport capacity of the system [2-3]. Therefore, solving the friction energy consumption of the supporting system of the conveyor has great effect on increasing economic benefits and energy saving and environmental protection.

To solve the friction energy dissipation problem of the supporting roller of the conveyor belt, many scholars at home and abroad applied air cushion type, cushion type and magnetic cushion supporting technology to the belt conveyor supporting system [4-7]. However, the air cushion type support has a large loss of pressure and poor supporting rigidity, and the cushion type support will make the conveyer belt slippery, reduce the driving force, and need additional water tank and water pump. G Cheng.et al analyzed the stability of magnetic levitation belt conveyor from the mechanical point of view, and then designed the structure of the belt conveyor. [8] K. J. Kim used a non-contact hybrid magnetic levitation system to replace the traditional roller system. The stiffness and damping characteristics of the supporting system are analyzed, and the corresponding tests are carried out in [9].

Scholars' research shows that the application of magnetic levitation technology to the supporting system of belt conveyor can effectively reduce energy consumption. Compared with the electromagnetic and hybrid magnetic levitation, permanent magnetic levitation is regarded as an effective way to reduce the energy consumption of idlers because of its advantages such as low cost, small size, no energy consumption, no control and maintenance. Yonnet J P studied the magnetic force, stiffness and torque of permanent magnetic bearings by the principle of virtual work. The mathematical model of permanent magnetic bearings under axial and radial magnetization is established [10-11]. The internal and external permanent magnetic rings of permanent magnetic bearings are equivalent to two cylinders, and the equivalent magnetic charge method is used to analyze the bearing capacity of the permanent magnetic bearings by the analysis of the axial magnetized radial permanent magnetic bearings in [12-14]. And N. Wang designed a horizontal axial MWTG supported with a permanent magnetic, the radial forces and the natural frequencies of the rotor system are studied [15]. A repulsion type magnetic bearing conveyor system is designed, and the structure and magnetic force of permanent magnet bearing with two axial and horizontal conditions are studied experimentally in [16-17].

In view of the problems existing in the application of magnetic suspension technology in the conveyor belt and the mature research of permanent magnetic bearings, this paper intends to apply the permanent magnetic bearing technology in the magnetic suspension bearing to the structure design of the conveyer belt roller, and make full use of the advantages of low energy consumption, noise free and no control of permanent magnetic bearings, so as to improve the transportation of the conveyor belt system. Efficiency, to minimize transportation energy consumption, to achieve energy saving and environmental protection purposes.

II. BEARING ANALYSIS OF MAGLEV ROLLER

The conveyor belt in the belt conveyor is connected to a closed loop, and the belt is tensioned with a tensioning device. Under the drive of the motor, the friction force between the conveyor belt and the driving roller makes the conveyer belt run continuously, to achieve the purpose of transporting the materiel. As shown in Fig.1.

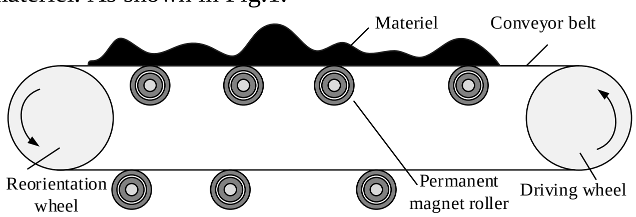

Figure 1. The mechanism model of belt conveyor

According the design Manual of DT II (A) belt conveyor, set the groove angle of a roller is 35°, the distance between the adjacent rollers is 5m, the quality of unit distance conveyer belt is 8.8kg, the quality of unit distance materiel is 44.2kg, the quality of the rotating part of the roller is 6.45kg. Then the carrying capacity of each segment is about 322.9N, the load of intermediate roller is 226N, and the load of two side rollers is 40N respectively.

Figure 2. The structure of mechanical roller

The structure of the mechanical roller is shown in Fig.2. Both sides of the mechanical roller are supported by mechanical bearings. The mechanical support can be changed into a magnetic suspension bearing. The structure schematic diagram of the maglev roller is shown in Fig.3.The main radial load of the roller is supported by the two permanent magnetic bearings (PMBs). The PMB on both sides are the same. However, according to Earnshaw's law, the radial PMBs are unstable in the axial direction and the benefit of the thrust ball bearing is to keep the maglev roller stable. The magnetic levitation force between the permanent magnet rings is used to realize the frictionless suspension and reduce the rotation resistance. This study only needs to design one side permanent magnetic bearing.

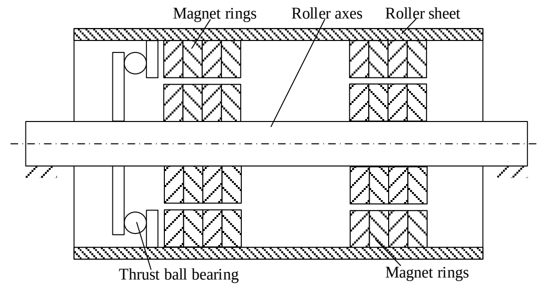

Figure 3. The structure schematic diagram of the maglev roller

III. LOAD CHARACTERISTICS OF THE MAGLEV RINGS

The axial-magnetization and axial-position PMB have been used in this roller. The mathematical model of the PMB is usually established by means of the equivalent magnetic charge method (EMCM) and the finite element method (FEM). The structure of the PMB is given in Fig.4 and the parameters of the cross section of the magnet ring is shown in Table I. The direction of the arrows are the polarization direction of magnetic rings. magnetic charges are uniformly distributed on the polarization direction surface of the magnet rings, where the positive magnetic charge is concentrated on the surface No.3 and the surface No.1, and the negative magnetic charge is concentrated on the surface No.2 and the surface No.4.

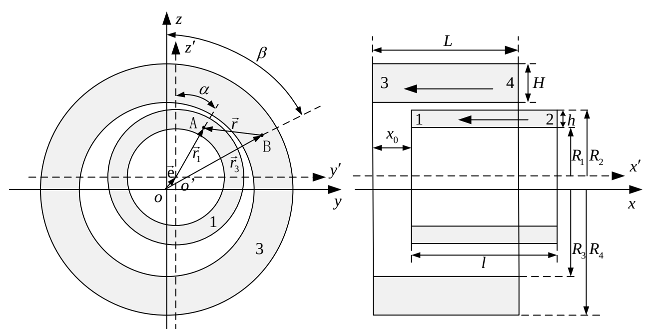

Figure 4. Axial-magnetization model of magnet ring

Table I. PARAMETERS OF CROSS SECTION OF MAGNET RING

Letter	Means
$\vec{r}_1, \alpha$	Polar coordinates of magnetic charge A
$\vec{r}_3, \beta$	Polar coordinates of magnetic charge B
$\vec{r}$	Radius vector of the magnetic charge A and B
e	Radial displacement of rotor
x_0	Axial displacement of rotor
R_1	Inner radius of inner magnet rings
R_2	Outer radius of inner magnet rings
R_3	Inner radius of outer magnet rings
R_4	Outer radius of outer magnet rings
l	Length of inner magnet rings
L	Length of outer magnet rings
H	Radial thickness of outer magnet rings
h	Radial thickness of inner magnet rings
g	Length of the air gap

According to the Coulombian's law, the magnetic force between the magnetic charge A and B is given in Eq.(1).

$$dF = \frac{1}{4\pi\mu_0}\cdot\frac{q_A\cdot q_B}{r^3}\cdot\vec{r} = \frac{1}{4\pi\mu_0}\cdot\frac{\sigma_A r_1 d\alpha dr_1\cdot\sigma_B r_3 d\beta dr_3}{r^3}\cdot\vec{r} \quad (1)$$

Where μ_0 is the magnetic permeability in the vacuum; q_A and q_B are the quantities of magnetic charge A and B; σ_A and σ_B are the density of magnetic charge A and B. Because the coercive force of NdFeB is large, according to the electromagnetic theory, the density of magnetic charges can be calculated using Eq.(2):

$$\sigma = B_r \quad (2)$$

Where B_r is the residual magnetic flux density of the magnetic material.

When both inner and outer magnetic rings are NdFeB materials, the repulsive force between the surface No.1 and No.3 of the magnetic rings can be calculated using Eq.(3).

$$\overline{F_{13}} = \frac{B_r^2}{4\pi\mu_0}\cdot\int_0^{2\pi}\int_0^{2\pi}\int_{R_1}^{R_2}\int_{R_3}^{R_4}\frac{r_1\cdot r_3\cdot\vec{r}d\alpha d\beta dr_1 dr_3}{|\overline{r_{13}}^3|} \quad (3)$$
$$|\overline{r_{13}}| = \sqrt{x_0^2+(e\cdot\sin\theta+r_1\sin\alpha-r_3\sin\beta)^2+(e\cdot\cos\theta+r_1\cos\alpha-r_3\cos\beta)^2}$$

So the radial magnetic force between surface No.1 and No.3 is given as:

$$\begin{cases} F_{13}^x = \frac{B_r^2}{4\pi\mu_0}\int_0^{2\pi}\int_0^{2\pi}\int_{R_1}^{R_2}\int_{R_3}^{R_4}\frac{x_0 r_1 r_3 d\alpha d\beta dr_1 dr_3}{|\overline{r_{13}}|^3} \\ F_{13}^y = \frac{B_r^2}{4\pi\mu_0}\int_0^{2\pi}\int_0^{2\pi}\int_{R_1}^{R_2}\int_{R_3}^{R_4}\frac{(e\cdot\sin\theta+r_1\sin\alpha-r_3\sin\beta)r_1 r_3 d\alpha d\beta dr_1 dr_3}{|\vec{r}_{13}|^3} \\ F_{13}^z = \frac{B_r^2}{4\pi\mu_0}\int_0^{2\pi}\int_0^{2\pi}\int_{R_1}^{R_2}\int_{R_3}^{R_4}\frac{(e\cdot\cos\theta+r_1\cos\alpha-r_3\cos\beta)r_1 r_3 d\alpha d\beta dr_1 dr_3}{|\vec{r}_{13}|^3} \end{cases} \quad (4)$$

Similarly, the radial magnetic force between surface No.2 and No.4 can be calculated:

$$\begin{cases} F_{23}^x = \frac{B_r^2}{4\pi\mu_0}\int_0^{2\pi}\int_0^{2\pi}\int_{R_1}^{R_2}\int_{R_3}^{R_4}\frac{(l+x_0)r_2 r_3 d\alpha d\beta dr_2 dr_3}{|\overline{r_{23}}|^3} \\ F_{23}^y = \frac{B_r^2}{4\pi\mu_0}\int_0^{2\pi}\int_0^{2\pi}\int_{R_1}^{R_2}\int_{R_3}^{R_4}\frac{(e\cdot\sin\theta+r_2\sin\alpha-r_3\sin\beta)r_2 r_3 d\alpha d\beta dr_2 dr_3}{|\overline{r_{23}}|^3} \\ F_{23}^z = \frac{B_r^2}{4\pi\mu_0}\int_0^{2\pi}\int_0^{2\pi}\int_{R_1}^{R_2}\int_{R_3}^{R_4}\frac{(e\cdot\cos\theta+r_2\cos\alpha-r_3\cos\beta)r_2 r_3 d\alpha d\beta dr_2 dr_3}{|\overline{r_{23}}|^3} \end{cases}$$
$$|\overline{r_{23}}| = \sqrt{(l+x_0)^2+(e\cdot\sin\theta+r_2\sin\alpha-r_3\sin\beta)^2+(e\cdot\cos\theta+r_2\cos\alpha-r_3\cos\beta)^2} \quad (5)$$

The bearing capacity of the internal and external magnetic rings should be the resultant force between the four ends. The force is positive when the magnetic charge polarity is same between two surface, the force is negative when the magnetic charge polarity is different between two surfaces. So the radial magnetic force between two magnetic rings can be calculated:

$$F = F_{13} + F_{24} - F_{23} - F_{14} \quad (6)$$

And the bearing force of one pair of permanent magnetic rings are given in Eq.(7):

$$F_r = \sqrt{F_y^2 + F_z^2} \quad (7)$$

According to the load characteristics study, the bearing characters have a relationship with the structure of the magnetic rings. Such as the axial displacement, radial displacement, the radius of the magnet rings, the length of the gap and so on.

Then this paper will used EMCM and FEM to simulate and analyze of the structure of permanent magnetic bearing for the roller.

IV. Simulation and Analysis of the Structure of Permanent Magnetic Bearing for the Roller

A. Simulation and analysis o by EMCM

Before simulate and analysis, set the radius of the roller sheet is 54mm, the inner radius of inner magnet rings is 15mm, and the outer radius of inner magnet rings is 25mm.

The relation curve of radial bearing force with the change of air gap is given in Fig.5. It shows that the smaller the air gap, the greater the radial bearing force of the permanent magnet rings; but the smaller the air gap is, the smaller the maximum radial displacement is, the smaller the maximum bearing capacity is. Therefore, considering the influence of size, assembly and delivery conditions, the value of g is preferred to be 2mm in the design of the magnetic rings.

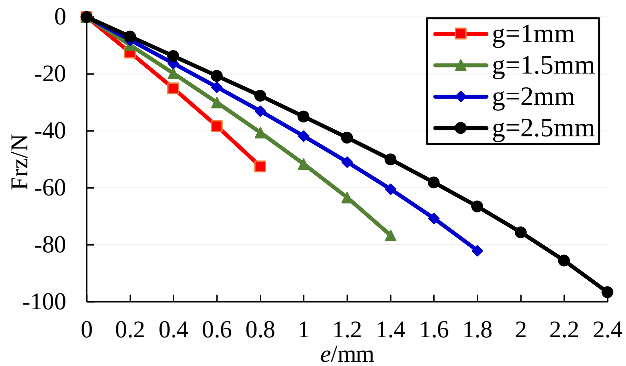

Figure 5. The relation curve of radial bearing force with the change of air gap

For radial permanent magnetic bearings, the width of the inner and outer magnetic rings in the radial direction is preferably the same or similar, the radial bearing stiffness is most suitable [13].

when the radial offset *e* changes within a certain range (g=2mm for example), the variation curve of radial bearing capacity is shown in Fig.6.

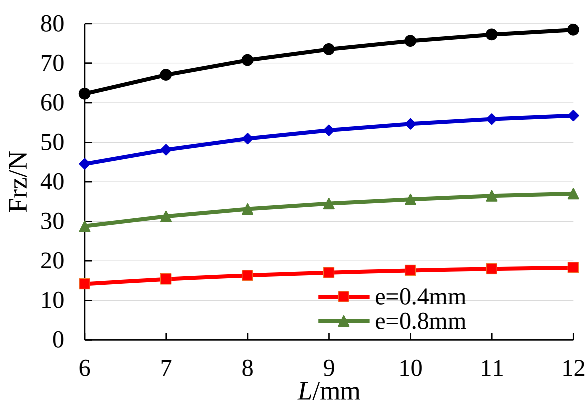

Figure 6. The relation curve of radial bearing force with the axis-length of the maglev ring

When the radial displacement *e* increases, the radial bearing capacity increases. When the radial displacement *e* is certain, if the axial length of the permanent magnetic ring is less than 8mm, the radial bearing force increases linearly with the increase of the axial length, but while the *L* is larger than 8mm, the radial bearing force is no longer linear with *L* and the change tends to be slow. Therefore, the axial length of the magnetic ring is preferred to be 8mm.

B. Simulation and analysis by FEM

Usually the bearing capacity of one pair of magnetic rings is small, and several pairs of magnetic rings will be used to increase the bearing force.

The load characteristics of the single permanent magnet ring have been analyzed theoretically, and the finite element method（FEM） can be used to simulate and compare the single permanent magnetic ring, so as to verify the rationality of the design of the single magnetic ring structure parameters. As shown in Fig.7.

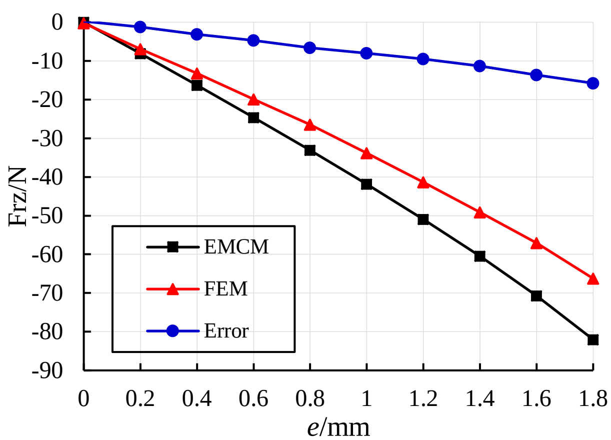

Figure 7. Comparison between EMCM and FEM for radial bearing capacity of single magnetic ring

From the diagram, the simulation results of EMCM and FEM show little difference, and the error is less than 15N. Therefore, the logarithm of the magnetic rings can be determined by FEM. The relation curve of the logarithm of the magnetic rings on the radial bearing force is given in Fig.8.

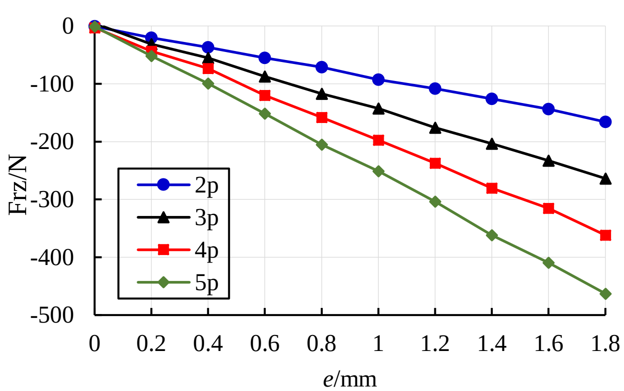

Figure 8. The relation curve of the logarithm of the magnetic ring on the radial bearing force

From the diagram, the more the logarithm of the magnetic rings, the larger the bearing force of the PMBs, the higher the cost of the magnetic roller. In the previous design of the magnetic roller, the size of the air gap is 2mm. While the radial displace is 1mm, select 4 pairs of the magnetic rings, the bearing force is about 197N. The resultant force of two PMBs can reach to 394N, which can meet the requirements of the bearing capacity of the magnetic roller.

The bearing force and bearing stiffness of PMB have a relationship with the axial displacement and radial displacement, respectively. The bearing capacity cave of this permanent maglev roller is given in Fig. 9. It shows the bearing radial bearing capacity of a PMB with 4 pairs of magnetic rings. When the axial deviation exceeds half of the axial length of the magnetic ring, the permanent magnet bearings will lose steady state.

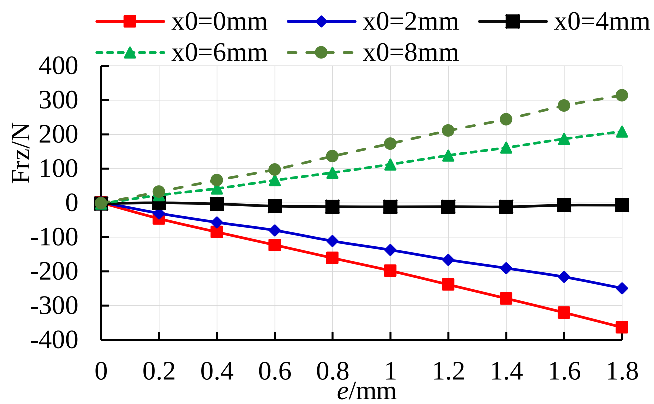

Figure 9. Bearing capacity cave of permanent maglev roller

Base on the simulation and analysis of the PMBs, the shape of the permanent maglev roller is shown in Fig.10. and the structure size of the maglev roller is shown in Table II.

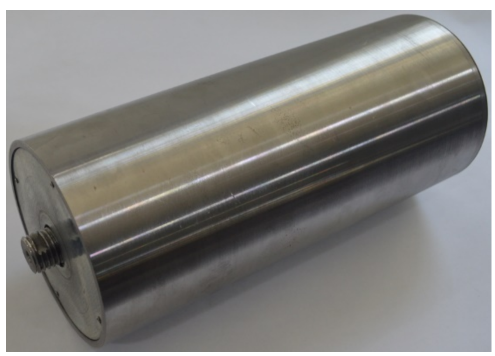

Figure 10. Shape of the permanent maglev roller

Figure 11. Outer magnetic rings and inner magnetic rings

Table II. THE STRUCTURE OF THE MAGLEV ROLLER

Parameter	Values
Diameter of roller	108mm
Length of roller	250mm
Logarithm of single side magnetic ring	4p
R_1	15mm
R_2	25mm
R_3	27mm
R_4	37mm
L / *l*	8mm
g	2mm

V. EXPERIMENT

The rotation drag of roller is the main reason causing the problem of large energy consumption and low speed in belt conveyor operation. To verify the rationality of the design of the magnetic suspension roller, it is necessary to test the rotation resistance.

According to the standard of GB821-2006, Put the maglev roller on the support rolls, the friction wheel is pressed on the roller, and the pressure is 250N. Start the electric machinery, the friction force of the friction wheel drives the rotation of the roller, keep the maglev roller's linear speed at 2m/s. after the roller rolling 1min, the rotary resistance indicator shows the rotation resistance.

In this research, the rotation drag of the maglev roller is 1.3N (air gap is 2mm and the number of the magnetic rings pairs is 4), which is much smaller than the standard of the mechanical idler (if the radius of the roller is 54mm, and the length of roller is shorter than 800mm, the rotation drag is below 2.5N).

When the external load is added, maybe the radial circle run-out of the maglev idler is larger than that of the mechanical idler because of the existence of air gaps. The radial circular run-out of the magnetic suspension roller needs to be measured to determine whether it meets the industrial requirements. The test of radial circle run-out is shown in Fig.12.

Figure 12. Test of radial circular run-out

Put the maglev roller on the radial circular run-out test, rotate the idler roller for a whole circle, and measure the radial circular jump momentum in the three axial positions, select the maximum value as the evaluation basis. The standard of the radial circular run-out is shown in Table III.

Table III. RADIAL CIRCULAR BEATING QUANTITY (mm)

Speed of band/m/s	Length of roller/mm			
	<550	>550~950	>950~1600	>1600~2400
>3.15	0.5	0.7	1.3	1.7
<3.15	0.7	1.00	1.5	1.9

According to the experiment results, the radial circular run-out of the maglev roller is about 0.18~0.25mm, less than the radial round jump of the high quality mechanical roller.

VI. CONCLUSIONS

In this paper, the maglev roller has been applied in the belt conveyor to reduce the friction resistance caused by friction resistance in the mechanical roller. The parameters of magnet levitation roller were optimized with finite element simulation.

The results show that bearing force of the maglev roller will be affected by many factors, such as the length of air gap, the axial displacement and the radial displacement of the magnetic rings, the number of magnetic rings pairs, and dimension of magnetic rings etc.

Finally, the performance test is carried out to verify the rationality of the design scheme. The research results show that the permanent magnet suspension supporting roller can effectively reduce the frictional resistance and reduce energy consumption in belt conveying.

REFERENCES

[1] S J Zhou, F Zeng, J Du, et al. "Experimental research on the energy consumption laws and its influencing factors of belt conveyor systems," *International Computer Conference on Wavelet Active Media Technology and Information Processing*, pp.395-402. 2016.

[2] G. Fedorko, and V. Ivančo. "Analysis of Force Ratios in Conveyor Belt of Classic Belt Conveyor," *Procedia Engineering* ,48.1,pp.123-128.

[3] G. Fedorko, V. Molnar, D. Marasova. "Failure analysis of belt conveyor damage caused by the falling material. Part II: Application of computer metrotomography," *Engineering Failure Analysis*, 34(8), pp.431-442, 2013.

[4] R. Król, W. Kisielewski, D. Kaszuba, and L. Gładysiewicz,"Laboratory tests of idlers rotational resistance – selected issues，"*Procedia Earth & Planetary Science*, 15, pp.712-719, 2015.

[5] S Guo, J Liu, Z R Li, et al,"Experimental research on air film formation behavior of air cushion belt conveyor with stable load," *Science China*, 56(6),pp.1424-1434,2013.

[6] Q H Dong, C Duan, Y Meng, et al. "Experiment and numerical simulation of pressure field for water cushion belt conveyor," *Journal of China Coal Society*, 37(11),pp.1930-1934(5). 2012.

[7] H U Kun, Y Liu, F Wang, et al. "Research on stability of suspension support system of permanent magnetic suspension belt conveyor," *Industry & Mine Automation*, 2018.

[8] G Cheng, Y C Guo, K Hu, et al. Magnetic Belt Conveyor Running Stability Analysis[J]. *Applied Mechanics & Materials*, 437, pp.682-685,2013.

[9] K. J. Kim , H. S. Han , C. H. Kim, and S. J. Yang, "Dynamic analysis of a maglev conveyor using an em-pm hybrid magnet，"*Journal of Electrical Engineering & Technology*，*8*(6), pp.1571-1578，2013.

[10] J. P. Yonnet, G. Lemarquand, and S. Hemmerlin, "Stacked structures of passive magnetic bearings,"*Journal of Applied Physics*, 70(10),pp.6633-6635,1991.

[11] J.P. Yonnet, S. Hemmerlin,and E. Rulliere. “Analytical calculation of permanent magnet couplings,” *IEEE Transactions on Magnetics*, 29(6), pp.2932-2934,1993.

[12] K. Bachovchin, J. Hoburg, and R. Post. “Stable levitation of a passive magnetic bearing,”*IEEE Transactions on Magnetics*, 49(1),pp.609-617, 2013.

[13] R. Ravaud, G. Lemarquand,and V. Lemarquand. “Force and stiffness of passive magnetic bearings using permanent magnets. Part 1 : Axial magnetization,” *IEEE Transactions on Magnetics*,45(7),pp.2996-3002, 2009.

[14] R. Ravaud, G. Lemarquand,and V. Lemarquand. “Force and stiffness of passive magnetic bearings using permanent magnets. Part 2 : Radial magnetization,” *IEEE Transactions on Magnetics*,45(9), pp.3334-3342, 2009.

[15] N. Wang, Y. Hu, H. Wu,J. Zhang,and C. Song. “Research on forces and dynamics of maglev wind turbine generator,” *Journal of Magnetics*, *18*(4), pp. 443-453. 2013.

[16] T. Ohji, S. Ichiyama, and K. Amei, “A new conveyor system based on a passive magnetic levitation unit having repulsive-type magnetic bearings,” *Journal of Magnetism & Magnetic Materials*, 272(272),pp.1731-1733, 2004.

[17] T. Ohji, S.C. Mukhopadhyay, and M. Iwahara, “Permanent magnet bearings for horizontal- and vertical-shaft machines: A comparative study,”*Journal of Applied Physics*, 85(8),pp.4648-4650,1999,.