Energy Efficient Rare Earth Lifting Permanent Magnet

N Ding, C Liu, J S Duan, S N Jiang and Y Q Hou
Mechanical and Vehicle Engineering College, Changchun University, Changchun 130022, China
dn33cn@163.com

Abstract. Nowadays lifting electromagnet is widely used in the world, but its fatal disadvantages are related to the electrical power input. A novel and energy efficient Rare Earth lifting permanent magnet is presented, which can completely overcome the lifting electromagnet disadvantages. In this paper, first, the developed optimization magnetic circuit design rule for Rare Earth lifting permanent magnet is discussed. Second, the lifting permanent magnet magnetic circuit design procedure is introduced. Finally, the invented mechanical drive system is expatiated. Industry prototype is manufactured, and it verifies that the proposed Rare Earth lifting permanent magnet is feasible.

1. Introduction
Lifting magnet is an important logistics handling equipment, which is used in cranes for handling ferromagnetic cargo or products, and widely used in seaports, stations and factories. However, ninety percent (90%) of the world’s lifting magnet equipment use electromagnets. In such apparatus, the electric current is passed through a large coil of a lifting head to produce a magnetic force. When the attracted ferromagnetic object need to be released, the current to the lifting head coil is cut off. However, electromagnetic lifting systems consume a large quantity of power due to the large current necessary to produce the magnetic force required. Furthermore, in the event of the power failure or cable fracture during a lifting operation, the attracted ferromagnetic object will fall from a considerable height. The lifting electromagnet cannot overcome the shortcomings by itself.

Lifting technology by using permanent magnet is one of the new applying fields. We have studied lifting permanent magnet for many years[1-3], which are energy efficient, and consume zero power. The Rare Earth lifting permanent magnet we designed can completely overcome the disadvantages found from lifting electromagnet. In this paper, first, the developed optimization magnetic circuit design rule for Rare Earth lifting permanent magnet is expatiated. Second, the lifting permanent magnet magnetic circuit design procedure is introduced. Finally, the invented mechanical drive system is presented.

2. Design of Rare Earth lifting permanent magnet
Rare Earth is used in the magnetic system as magnetic resource. The lifting permanent magnet we designed consists of magnetic circuit system and mechanical drive system, as shown in figure 1. The magnetic circuit system is composed of movable, the immovable magnet subsystems and magnetic yokes. The movable magnet subsystems can rotate around their own axis, and the working magnetic pole surfaces can obtain doubled or cancelled magnetic field intensity. Then the Rare Earth lifting permanent magnet realizes attracting or unloading the ferromagnetic object, as shown in figure 2-4.
2.1. Study of magnetic circuit system design

2.1.1. Design rule of lifting permanent magnet magnetic circuit. By now, the study of permanent magnet lifting is only towards the start of industrial application. In order to completely replace lifting electromagnet, we should study optimal magnet circuit design rules first.

During the magnet circuit design, the permanent material working point is the basis, and is also the key to determine whether the magnet circuit design is economical and reasonable. The change of working point along the PhDBP of recovery curve as shown in figure 5 and figure 6. From figure 5, we get the following equation:

\[ \mu_{rec} = \frac{B_u - B_f}{H_p} \]  \hspace{1cm} (1)

Here, \( \mu_{rec} \) is the recoil magnetic reluctance coefficient.

When there is a gap between the attracted object and the work magnetic pole surface of Lifting permanent magnet, we can get the following

\[ \Phi = B_m S_m = \Phi_u + \Phi_f = (B_u + B_f) S_m \]  \hspace{1cm} (2)

Here, \( \Phi \) is the permanent magnet flux. \( B_m \) is the magnetic flux density. \( S_m \) is the neutral surface area of permanent magnet. \( \Phi_u \) is useful flux. \( \Phi_f \) is the leakage magnetic flux. \( B_f \) is magnetic flux density.
Here, $P_f$ is Magnetic flux leakage conductance. From figure 5 and figure 6, the following equations can be obtained:

$$P_f = \frac{B_p S_m}{H_p L_m}$$

$$P_f = \frac{B_p S_m}{H_p L_m}$$

Where, $H_m$ is the demagnetization density of the permanent magnet when the position of attracted object is shown in figure 5 and 6. $L_m$ is the length of permanent magnet. When the attracted object is removed, the working point of permanent magnet is at $P(B_p, H_p)$. $B_p$ is flux leakage density, and $P_f$ is the same as that when the working point is at $E(B_m, -H_m)$, i.e.

$$E_{rec} = (B_p + \mu_{rec} H_p) H_p - \frac{(B_p + \mu_{rec} H_m)^2}{2}$$

Take the maximum value of $E_{rec}$ to $H_m$ and get

$$H_m = \frac{1}{2} H_p$$

That means when $H_m$ equal to half of $H_p$, that is, when $E$ is at midpoint, the useful recovery energy at $P$ can reach the maximum value $(E_{rec})_{max}$.

$$E_{rec} = \frac{1}{4} H_p^2 - \frac{1}{2} B_p H_p = \frac{1}{2} S_{\Delta OPD}$$

In the formula, $S_{\Delta OPD}$ is area of $\Delta OPD$. According to equation (6), the useful recovery energy changes with initial working point $P$, and the limit value of the possible recovery energy is different with different point $P$. Therefore, the start point $P$ must be properly selected to obtain the maximum useful recovery energy $(E_{rec})$ of permanent magnet.

According to the first and the second basic equation of magnetic circuit, the relationship between recovery energy and magnetic attraction force can be obtained:

$$F = \frac{1}{8\pi} B_s H_s S_e = \frac{L_m S_m}{4\pi K_p L_g} B_s H_s = \frac{V_n}{4\pi K L_g} E_{rec}$$
Where, $V_m$ is the volume of permanent magnet. It can be seen from the equation (7) that the magnetic attraction force proportional to the recovery energy $E_{rec}$. For general permanent magnet material, starting point $P$ should be selected below the maximum magnetic energy product $(BH)_{Max}$ point to enable the useful recovery energy to reach the maximum value. Only in this way can permanent magnet materials be fully utilized, and have greater magnetic attraction force. For rare earth isotropic permanent magnetic materials, the demagnetization curve is a straight line, so the maximum magnetic energy product $(BH)_{Max}$ point should be taken as the starting point. All in all, the reasonable selection of working point is the rule to be followed in the design of lifting permanent magnet

2.1.2. Design procedure of lifting permanent magnet magnetic circuit. The method of magnetic conductance is used in the design of the Rare Earth lifting permanent magnet magnetic circuit. In general, the lifting capacity and the dimensions are required by the user, and we determine the area of working magnetic pole surface. First, we select the magnetic material used in the movable magnetic system and immovable magnetic system. Then we calculate the lifting ratio and from this the volume of the permanent magnet can be determined. Third, the total magnetic conductance of the movable magnetic system and immovable magnetic system are calculated by the following formula:

$$\frac{B_m}{H_m}=\frac{PL_m}{\mu S_m}.$$ (8)

Here, $P$ is the total magnetic conductance, $\mu$ is magnetic reluctance coefficient.

Fourth, we substitute $L_m$, $S_m$ and $\mu$ into the equation (8), and find $B_m$, $H_m$ from the demagnetization curve of magnet. Fifth, the total magnetic flow $\Phi$ is calculated, and the $\Phi_1$ of the working magnetic pole surface can be obtained.

$$\Phi_1=\Phi \cdot \frac{P_1}{P}.$$ (9)

Sixth, the magnetic intensity of the movable magnetic system and immovable magnetic system on the working magnetic pole surface are determined. For different $L_m$ and $S_m$, the different magnetic field intensity can be calculated. Finally we can get the close to zero (0A/m) in the unloading condition. The magnetic field intensity between the working magnetic pole surface and the surface of the attracted object can also be obtained.

2.2. Design of mechanical drive system
The magnetic circuit design only guarantees that the Rare Earth lifting permanent magnet can attract the ferromagnetic object economically. However, how to load-off the attracted object fast and conveniently is a problem. Many researches have done about unloading methods[4-5]. Motor and speed reducer, electrical pulse, reverse magnetization are used, but they also consume electricity energy. We invented a mechanical drive system, which can changes the lifting hook’s upward traction force into the movable magnetic system rotating moment, and consume zero power.

The drive system structure is shown in figure 1 and figure 7.

The work process of lifting the object is as follows:

When the lifting hook is lifted, the small chain 1 is strained; the swing stem 2 rotates 60 degree. At the same time the axis 6 is also rotated 60 degree by the ratchet pawl. And the small gear wheel axis is rotated 180 degree because the drive ratio of the small gear wheel 4 to the big gear wheel 5 is 3:1. This time the magnetic field intensity is doubled on the magnetic pole surface, which will allow lifting permanent magnet to attract the ferromagnetism object, and then lift and carry it to the destination.

The work process of unloading the object is as follows:

When the lifting permanent magnet puts the attracted object down, the swing stem 2 and the ratchet pawl slide down to the next gullet. The axis 6 does not rotation. When the lifting hook is lifted once more, the swing stem 2 rotates 60 degree. At the same time the axis 6 is also rotated 60 degree by the ratchet pawl. And the small gear wheel axis is rotated 180
degree. The magnetic field intensity is cancelled on the magnetic pole surface, which makes it possible that lifting permanent magnet can unload the attracted load.

3. Experiment verification
We designed and manufactured the industry prototype of Rare Earth lifting permanent magnet, as shown in figure 8. Its length is 0.9m, and the width is 0.8m. The gap required between the attracted object and the working magnet pole surface is 0.002 m, and magnetic induction is 2 wb/m in the gap. Its magnetic attraction force is 6 ton, and residual magnetic field intensity is 43.3Oe in unloading condition.

4. Conclusion
The proposed lifting permanent magnet is a kind of energy efficient product, which can completely eliminate the disadvantages found in conventional lifting electromagnet. In this paper, the optimization magnetic circuit design rule and procedure is expatiated. Besides, the invented mechanical drive system is presented, which can make the lifting permanent magnet attract and unload the object automatically without consumption any electricity at all.

Acknowledgments
The authors would like to acknowledge funding support from Jilin Province Industrial Technology Research and Development Project(Grant No. 2018C043-2).

References
[1] Ding N, Zhang D T and Song Y M 2013 *Adv. Mater. Res.* **662** pp 653–6
[2] Ding N, Song Y M and Wang L N 2013 *Adv. Mater. Res.* **655-658** pp 355–8
[3] Pei Y Z and Ding N 2011 *J. Changchun Univ.* **8** pp 10–2
[4] Ken M 2017 *Scrap* **74**(6) pp 73–7
[5] Jean-Rene G 2015 *SMM: Schweizer Maschinenmarkt*, **116**(25-6)