Structure Optimization Design for Electromagnet on EPLA Electro-Pneumatic Change Valve

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***Abstract*—This paper introduces the structure and working principle of the EP valve electromagnet. The electromagnet model is established by Ansoft software to analyze the influence of each component structure on the output performance of electromagnet and then to optimize the structure of electromagnet. Through joint simulation with Ansoft and AMESim software, a multi-physical field model of EP valve is established, which verifies the feasibility of electromagnet structure optimization and provides a new idea for the design of domestic electromagnet.**

Keywords—EP valve; electromagnet; parametric design; multi-physical field modeling

I. INTRODUCTION

The braking system is one of the most important systems of the high-speed train. At present, the braking system on the high-speed train mainly consists of two types: switch type and analog type. The electro-pneumatic change valve used in China's CRH2 and CRH6 braking system is an analog electro-air shutoff valve, also known as EPLA electro-pneumatic change valve (EP valve). Electromagnet is the core driving component of EP valve and its structure design directly affects the output performance of the EP valve. At present, a large number of EP valve electromagnets are imported products, which are expensive and lack of core technical parameters. Therefore, it is of great significance to optimize the structure of the electromagnet to guide the domestic design.

The internal structure of an electromagnet is complicated due to the coupling environment of electro-magnetic-force-thermal multiple physical fields, so the traditional numerical calculation is difficult and inaccurate. Therefore, this paper adopts Ansoft software to analyze the output characteristics of electromagnet under different structures by parameterization, so as to optimize the structure of electromagnet and to provide the theoretical basis for further improvement of design. At the same time, through the joint simulation of Ansoft and AMESim, multi-physics field modeling is carried out to test the feasibility of the optimized design.

II. ELECTROMAGNET STRUCTURE AND WORKING PRINCIPLE

A. EP valve structure

The EPLA electro-pneumatic change valve (EP valve) is used as a pre-control pressure control valve in braking systems. According to the linear relationship between input current and output pressure, the electric command is converted into air pressure and output to the relay valve. The pre-control chamber of the relay valve has a certain compressed air, which can control the common brake pre-control pressure in a continuously stepless section. The EP valve is mainly composed of an electromagnet, a plunger, a return spring, a corrugated diaphragm, an exhaust piston, a supply-exhaust valve and a supply-exhaust valve spring [1], and has three passages for supplying air, acting instruments, and exhausting air. The electromagnet is responsible for providing electromagnetic force and is the core driving component of the EP valve.

B. EP valve electromagnet working principle

The structure of the EP valve electromagnet is as shown in Fig. 1, it is comprised of a static iron core 1, a plunger 2, an upper cover 3, a magnetic core 4, a coil 5, a bushing 6, a movable iron core 7, a spacer 8 and a lower cover 9.

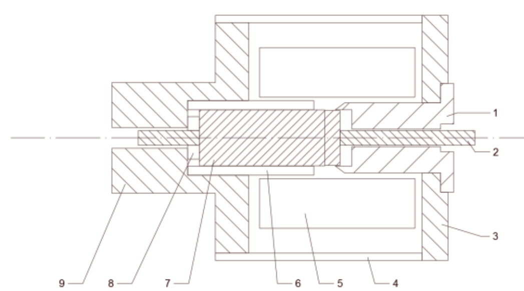

Figure1. Electromagnet structure.

The electromagnet is a force-controlled proportional electromagnet, which differs most from ordinary DC electromagnets in electromagnetic force characteristics. The proportional electromagnet has a horizontal electromagnetic force characteristic, that is to say, its output electromagnetic force is proportional to the input current, regardless of the displacement. When the current flows through the coil, two magnetic circuits are formed under the action of the magnetic potential. The magnetic circuit φ_1 passes through the bottom of the static iron core, enters the movable iron core along the axial working air gap, bypasses the lower cover and then returns to the forepart of the static iron core through the magnetic core. The other magnetic circuit φ_2 passes through the radial working air gap from the periphery of the static iron core's

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chamfer into the movable iron core, and then merges with φ_1. The magnetic circuit φ_1 and φ_2 work together to keep the electromagnetic force of the electromagnet and the displacement of the movable iron core substantially horizontal [2].

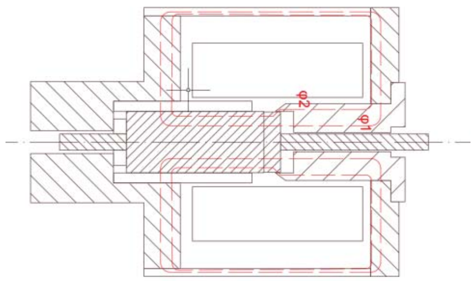

Figure2. Electromagnet magnetic circuit.

III. Electromagnet Ansoft Maxwell 2D Modeling

A. Static magnetic field analysis

A static magnetic field is a magnetic field that does not change with time. It usually includes the magnetic field of a permanent magnet, the magnetic field generated by a steady current, the magnetic field created by an external static magnetic field, and the conductor that moves at a constant speed. The field equation for the magnetic position vector A in the static magnetic field solver is as follows:

$$J_z(x,y) = \nabla \times (\frac{1}{u_r u_0}(\nabla \times A_z(\mathrm{x},\mathrm{y}))) \tag{1}$$

$A_z(\mathrm{x},\mathrm{y})$ is the Z-axis component of the magnetic position vector, $J_z(x,y)$ is the current density of the current flow section, u_r is the relative permeability of the material in the solution domain, and u_0 is the permeability in vacuum rate.

According to the given excitation source $J_z(x,y)$, the static magnetic field solver can calculate the magnetic position vector of each point in the solution domain, and then solve the magnetic induction and magnetic field strength[3].

B. Electromagnet Maxwell 2D Model

The electromagnet is modeled by Ansoft Maxwell 2D. Because the electromagnet is of axisymmetric structure, the cylindrical coordinate system is used to establish the half model of the electromagnet, which can save the calculation time without affecting the calculation accuracy.

1) Geometric Modeling

According to the electromagnet drawing in [4] and combined with the disassembly and measurement of the EP valve, the 2D geometric model of the electromagnet is established and imported into Ansoft.

2) Definition of materials

The materials of each part of the electromagnet model are defined according to the description requirements of the materials of the electromagnets in [4].

3) Boundary and excitation settings

a) Using infinite boundary condition (balloon boundary conditions) to save computing resources;

b) A positive current excitation is applied to the coil, and the number of coil turns is 3300.

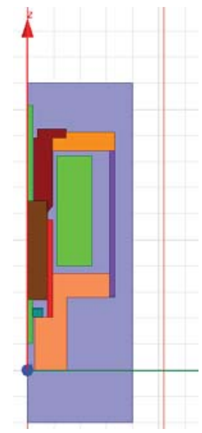

Figure3. Electromagnet model.

TABLE I. Materials of various parts of the electromagnet

Components	Materials
bushing; cover; static iron core	cold rolled steel
coil	copper
movable iron core	DT4
magnetic core	steel 1008
plunger; spacer	stainless steel

4) Meshing and solving settings

a) Considering the actual size of the electromagnet, we use Length based on Selection Mesh Operation and set the Maximum Length of Elements to 10 mm;

b) Using the static magnetic field solver, the maximum step size is set to 12 and the percentage error is 0.05;

c) Setting the Optimetrics: the drive current is increased from 0.2A in steps of 0.1A to 0.65A, and the air gap (axial distance between the static iron core and the moving iron core) is from 0mm in steps of 0.5mm to 6mm.

5) Simulation results

As can be seen from Fig. 4, the electromagnetic force of the electromagnet increases with increasing drive current; the electromagnetic force exhibits a horizontal characteristic in the range of 3 mm to 6 mm of the air gap, which can be used as its working stroke. But when the current exceeds 6A, the electromagnetic force amplitude is upturned in the range of 3 mm to 4 mm and losses its horizontal characteristic.

During the working stroke of the electromagnet, when the current is 0.2A, the simulated electromagnetic force is 39N; when the current is 0.65A, the force is 194N. The error between the simulation results and the electromagnet performance standard (0.2A 35N and 0.65A 193N) given in [4] is less than

12%, indicating the accuracy and reliability of the simulation results.

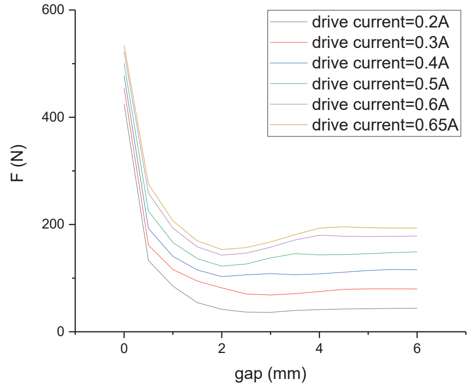

Figure 4. Electromagnet simulation results.

IV. PARAMETRIC SIMULATION ANALYSIS OF ELECTROMAGNET PART STRUCTURES

The selection of materials and coil turns will have a great influence on the output performance of the electromagnet. Therefore, the electromagnet has been strictly designed and verified in conjunction with the actual application needs before delivery. However, from the simulation results in Section 3.2.5, it can be seen that with the increase of the drive current, the electromagnetic force amplitude shows an upward trend in the range of 3mm to 4mm, and the electromagnetic level characteristic deteriorates. So the output pressure of the EP valve will also be affected. Therefore, by performing parametric simulation analysis in Ansoft, the influence of the bushing and the static iron core's shape on the electromagnetic force of the electromagnet is studied under the condition of a drive current of 0.6 A. Through the partial adjustment of the structure of the electromagnet, the optimization scheme for improving the horizontal characteristic of the electromagnetic force is explored, and then the reference for the local optimization of the electromagnet is provided without changing the overall structure.

A. *Influence of bushing length on electromagnetic force*

On the basis of the model in Section3, reducing the length of the bushing which means increasing the axial distance between the bushing and the static iron core. The length of the bushing is further reduced from 0 mm to 7 mm in steps, and the step length is 1 mm.

As the length of the bushing is reduced, the electromagnetic force drops, and the electromagnetic force level characteristic degrades within a working stroke of 3mm to 4mm. The reason is that there is a radial air gap between the bushing and the movable iron core. As the length of the bushing is shortened, the range of the radial air gap becomes smaller, and the electromagnetic force generated by the magnetic circuit φ_2 trails off. However, in the range of 4mm to 6mm working stroke, the electromagnetic force amplitude of the electromagnet under different bushing lengths doesn't change substantially.

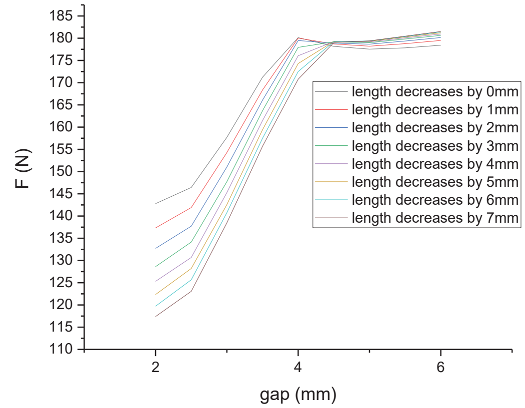

Figure 5. Bushing length influence on electromagnetic force

B. *Influence of bushing width on electromagnetic force*

Based on the initial model in Section3, reducing the width of the bushing to increase the gap between the bushing and the movable iron core, and the gap varies from 0mm to 1mm in steps of 0.2mm on the basis of the original 0.1 mm.

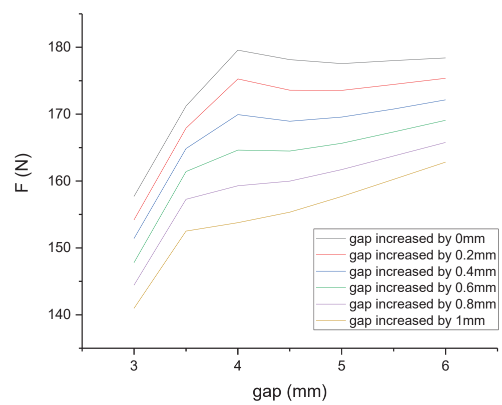

Figure 6. Bushing width effect on electromagnetic force

The electromagnetic force on the plunger decreases as the gap between the bushing and the movable core increases. However, the horizontal characteristic of the electromagnetic force is improved: when the gap between the bushing and the movable iron core is 0.1 mm, the maximum fluctuation of the electromagnetic force in the working stroke of 3.5 mm to 4 mm is 8.32 N (4.9%), and when the gap increases to 1.1 mm, the maximum fluctuation of the electromagnetic force in the above working stroke is 1.25 N (0.8%).

C. *Effect of static iron core shape on electromagnetic force*

Upon the model in Section3, the chamfer shape of the static iron core is changed, and the radial gap between the movable iron core and the chamfer of the static iron core is gradually increased in three steps.

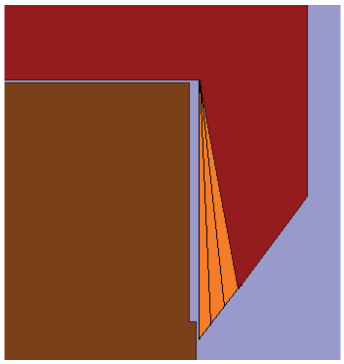

Figure 7. Static iron core shape change diagram.

In Fig.8, F_initial is the electromagnetic force obtained under the initial structure. F_change1, F_change2 and F_change3 are the electromagnetic forces obtained by continuously increasing the radial clearance between the movable iron core and the static iron core chamfer. It can be seen that the amplitude uplift characteristic of the electromagnetic force in the working stroke of 2.5 mm to 4 mm is improved.

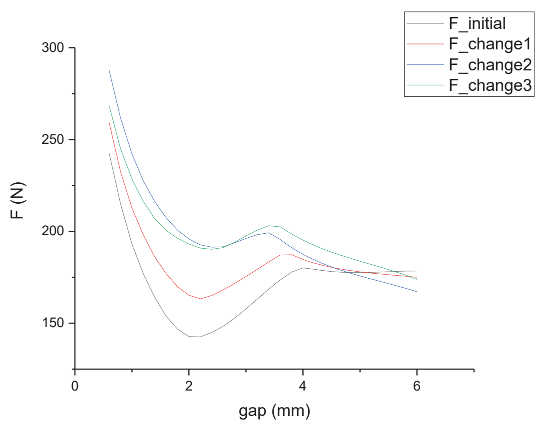

Figure 8. Effect of static iron core shape on electromagnetic force.

However, when increased radial clearance is too large, it will lead to the electromagnet force declining trend. The reason is that as the moving iron core gradually moves away from the static iron core, the electromagnetic force F_1 generated by the magnetic circuit φ_1 gradually decreases, and at the same time, the electromagnetic force F_2 generated by φ_2 gradually increases.

When the ratio between the radial clearance of the chamfer of the static iron core and the active iron core is small, the increase of F_2 exceeds the decrease of F_1, and the superposition is reflected on the electromagnetic force curve as upturning. By continuously adjusting the chamfered shape of the static iron core, the radial air gap of φ_2 is increased at an appropriate position to slow the increase of F_2, and the horizontal characteristic of the electromagnetic force can be improved.

V. Optimized Design Inspection

A. EP valve modeling

Combining the electromagnet model in Ansoft, relying on the Pneumatic Component Design (PCD) library, the Mechanical library and the Electric Storage (ES) library in AMESim to build a complete EP valve model to achieve the coupling between electro-mechanical-magnetic multi-physics [5,6].

EP valve model consists of voltage source 1, electromagnet 2, plunger 3, exhaust piston 4, corrugated diaphragm 5, intake port 6, supply-exhaust valve spring 7, air source 8, relay valve volume chamber 9, piping 10 and the orifice 11.

The electromagnet uses the EMLTR01 module in the ES library, and the data of the electromagnetic force and inductance with the air gap and ampere-turns calculated by Ansoft are input into AMESim in the form of 2D Table, and the resistance is set to 26.6 ohms.

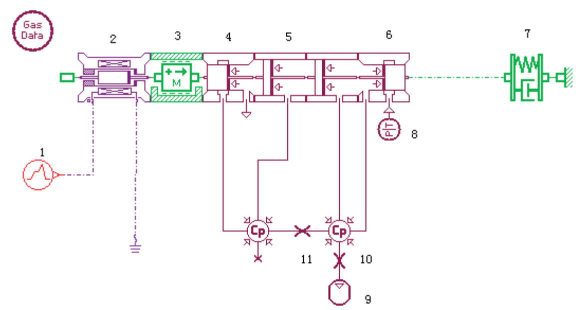

Figure 9. EP valve complete model.

Set the voltage source excitation from 0 to 13.3V in 1 second and the voltage constant at 13.3V after 1 second to obtain the EP valve pressure output curve. After 1.7 seconds, the output pressure is constant at 4.3745barA (437.45kPa). The pressure-current calculation formula P(kPa)=1.4514*I(mA)-282.43 given in [1] calculates the expected pressure value, which is 443.27kPa. The difference between the two is 5.82kPa, within the normal error range, which also verifies the accuracy of the EP valve model.

B. Analysis of output performance of EP valve after optimization

According to the analysis of the structure of each part of the electromagnet in Section4 and on the basis of the model in Section3, the gap between the bushing and the movable iron core is increased by 0.75 mm, and the shape of the static iron core is modified to increase the movable iron. The radial clearance between the movable iron core and the static iron core chamfer is up to the shape corresponding to F_change2 in Section4.3. The results from the simulation in Ansoft are then input to AMESim again in 2D Table format.

According to the comparison of the output pressure of the EP valve before and after the improvement in Fig.10, the EP valve reaches the steady state at a faster rate, reducing the response time by 0.4 seconds.

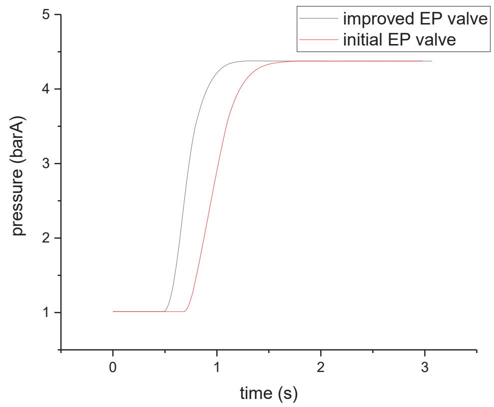

Figure 10. Comparison of EP valve output pressure before and after improvement.

VI. CONCLUSION

In this paper, by establishing the electromagnet model in Ansoft Maxwell 2D, the influence of bushing and static iron core structure on the output characteristics of electromagnet is analyzed, and then the optimimal design method of electromagnet structure is explored. The simulation results show that increasing the gap between the bushing and the movable iron core within a certain range can enhance the electromagnetic force level characteristic, and changing the chamfer shape of the static iron core can improve the uplift of the electromagnetic force in the middle working stroke.

At the same time, through the joint simulation of Ansoft and AMESim, the multi-physics model of EP valve is established, and the coupling solution of electro-mechanical-magnetic multi-physics is realized. The simulation results prove that the EP valve model has good dynamic characteristics and tracking performance, and the model output approaches the design value. The output response of the EP valve with optimized electromagnet is obviously improved, which verifies the rationality of the optimized design.

In a word, this paper provides a reference for the optimization design of solenoid valves by exploring parametric design and multi-physics modeling methods, which in turn provides an architecture for digital product design.

ACKNOWLEDGMENT

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REFERENCES

[1] “EPLA electric-pneumatic change valve instruction manual. Nabtesco Corporation Railway Technology Department,” unpublished.

[2] Fang Xiang and Wei Jianhua, “Simulation Research on Improving the Stroke Force Characteristics of Proportional Electromagnet,” Machinery Design. Tianjin, vol. 27, pp. 19-20, December 2010.

[3] Zhao Bo and Zhang Hongliang, Application of Ansoft12 in engineering electromagnetic field, Beijing: China Water Resources and Hydropower Press, 2010.

[4] “Electro-pneumatic change valve solenoid installation manual. Nabtesco Corporation Railway Technology Department, ” unpublished.

[5] Cai Shengnian, Chen Long, and Xu Chengyu, “Multi-physical Modeling of Proportional Solenoid Valve Based on Ansoft and AMESim,” Machine Tool & Hydraulics. Guangzhou, vol. 42, pp. 169-173, December 2014.

[6] Wang Chunmin, Sha Chao, and Wei Xuefeng, “Simulation Analysis of Dynamic Characteristics of Direct Acting Solenoid Valve Based on AMESim and Ansoft,” Machine Tool & Hydraulics. Guangzhou, vol.45, pp. 160-163, November 2017.