Investigation on the electromagnetic centring technique in compressor with labyrinth seal structure

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Abstract. At present, the piston of compressors with labyrinth seal structure generally runs eccentrically, which causes uneven radial clearance, serious leakages and lower volumetric efficiency. This has become an urgent problem in the development of labyrinth compressors. In this study, electromagnetic levitation technology was introduced to achieve concentric centering between the piston and cylinder, and the conventional cantilever structure for the piston centering was replaced by a simple support structure using the through-piston rod. Furthermore, the simulation model of the electromagnetic centering system was established and the experimental prototype was built. The mathematical simulation model was verified by comparing simulated and tested results. Then, the centering effect of the system was assessed and the variation of the leakage in the compressor was studied by models using dynamic mesh technology. The results showed that the radial clearance between piston and cylinder can be maintained in the range of -0.3 mm to 0.3 mm through the electromagnetic centering control. In addition, the inner leakage of the compressor was quite appreciable without the electromagnetic control. However, it was reduced by 1.8 times with the introduction of the electromagnetic control. Thus, it can be concluded that the precise centering between the piston and the cylinder can be achieved by the introduction of the electromagnetic centering technique.

1. Introduction

In a labyrinth piston compressor, the labyrinth seal is adopted between piston and cylinder mirror, piston rod and cylinder-seat [1,2]. This sealing structure not only can ensure the compressed gas oil free, but also avoid the production of dust and debris in the cylinder. More importantly, if the gas is flammable and explosive, or toxic, the compressor has high safety and reliability [3]. Currently, with the development of the petroleum and chemical industry, the labyrinth piston compressor has been widely used in oil refining, pharmaceutical, metallurgy, military and other industries.

Because of using labyrinth seal in the process of design and manufacture of reciprocating compressor, the serious inner leakage and low volumetric efficiency are the major obstacles for wide application of the labyrinth piston compressor. The design of the labyrinth structure, the eccentric running of the piston, the design of radial clearance between piston and cylinder wall and other factors can cause the labyrinth piston compressor serious inner leakage [4,5]. Among of them, maintain coaxial centering between piston and cylinder is the most critical problem. In the current labyrinth piston compressor, the piston is always guided by the crosshead and the guide bearing which causes piston’s eccentrically running and friction between the piston and cylinder in the actual working process [6]. Therefore in order to avoid friction between piston and cylinder wall, the larger value of
radial clearance between piston and cylinder wall should be taken. But the larger value of radial clearance between piston and cylinder caused the compressed gas serious inner leakage which caused the volumetric efficiency low and made a great waste of energy [7].

In order to solve these problems, many scholars have done a lot of research related to the labyrinth’s structure, the piston shape, and installation position of the guide bearing, etc. But the problems of piston eccentric operation and lower volumetric efficiency of the compressor still has not been effectively resolved [8-12].

To solve these problems, through an in-depth and detailed analysis, this thesis try to adopt the reciprocating magnetic levitation technology to realize the concentric centering of the labyrinth piston. So that the clearance between the piston and the cylinder mirror can be remarkable reduced without scraping, and the inner leakage will be greatly decreased and the volume efficiency of the compressor will be greatly improved. By looking up a large number of the relevant research information, the magnetic levitation technology has been successfully applied in turbine machinery, but there are still no reports on the application of magnetic levitation technology to the reciprocating machinery [13-15]. The research topic of this thesis not only relates to the radial movement of the piston, but also related to the steady flow in the labyrinth clearance, and it is more related to the study on nonlinear electromagnetic dynamics of reciprocating magnetic levitation technology.

The main research works and main results obtained in this thesis are as follows: the electromagnetic levitation technology was first used to realize concentric centering between the piston and cylinder and the transfer function model of the centering systems was derived and the simulation model of the electromagnetic centering system was established by matlab/simulink. And the traditional cantilever structure for the piston centering was transform into the simple support structure by using the through-piston rod; Considering the clearance between crosshead and slide-way, piston rod and guide bearing, the radial deflection equation of the piston with crank angle was deduced through the movement relationship of the piston and the piston rod system; In order to verify the model correctness and centering effect of the electromagnetic centering system, an experimental platform of the electromagnetic centering system based on the core of DSP was designed and built; An unsteady flow-field and leakage analysis model of multi-labyrinth was established by the commercial FEM software, and the modified turbulence model (RNG)k-ε was applied to investigate the changing regularity of the pressure distribution and flow pattern.

2. Theories and models of the investigation

2.1. Electromagnetic guiding theory

At present, the cantilever structure of labyrinth piston compressor is main used to suppressing the piston’s eccentric running. The radial clearance exists between the crosshead and the slide-way, also between the guide bearing and the piston rod. As mentioned above, it is very difficult for the proposed cantilever structures to realize the piston’s precision centering. In order to solve this problem, an electromagnetic guiding system is introduced in this paper.

The new structure adopts the through-piston rod as shown in figure 1. This kind of structure can ensure that the piston and piston rod with the same radial eccentric motion law. On the top of the cylinder set up the radial magnetic orientation structure around the guide bar to restrain and control the guide bar radial eccentric movement. The improved structure can not only realize coaxial centering of the piston and piston rod but also simplifies the traditional cantilever structure.

Electromagnetic centering control mode is heavily dependent on the attraction of the electromagnetic coil on the guide bar, and according to the actual location of the guide bar, energized by adjusting the control current of coil to control the size of the force on the guide bar.
1. Guiding sleeve 2. Filler sleeve 3. Upper piston rod 4. Piston 5. Oil retainer 6. Crosshead 7. Slide-way

**Figure 1.** The diagram of piston centering by electromagnetic guiding system.

The active electromagnetic control system adopt in this paper is mainly composed of displacement sensor, power amplifier, PID, the electromagnetic coil, controlled object, etc. They form a closed loop system. Displacement sensor is mainly used for real-time detection of controlled object, feedback control signal to control system. PID is mainly to control the operation and output feedback signal. According to the different functions, the design of electromagnetic centering control system includes the design of the electromagnetic actuator and control system design. Electromagnetic actuator mainly includes power amplifier and the radial electromagnetic coil two parts as shown in figure 2. The reasonable parameters design of radial electromagnetic coil structure is one of the prerequisites to ensure that bearing capacity and realize stable suspension of the object. According to the guide bar’s motion characteristics, the axial reciprocating motion do not control and there are two degrees of freedom need to control in the radial direction of the guide bar. In order to realize the active control in the direction of the degrees of freedom, every radial degree of freedom needs a set of actuators, which makes the guide bar by electromagnetic attraction on positive and negative direction in each radial degree of freedom. In this article, the electromagnetic coil using the structure of circular groove and the round wire, as shown in figure 3. There are eight poles in electromagnetic coil and the adjacent two make a group. Therefore, the electromagnetic coil is actually made up of four pole pairs and there are two pole pairs in the direction of each degree of freedom.

**Figure 2.** The working principle of electromagnetic control system.
Assume the air gap of magnetic coil is uniform, according to the field theory and virtual displacement principle, the electromagnetic force is given in equation 1. Where \( N \) is the coil number of turns, \( I \) is the current, \( \delta \) is air gap. According to the equation 1,

\[
f = \frac{\partial W}{\partial \delta} = \frac{B^2A}{\mu_0} = \frac{1}{4} \mu_0 N^2 A \cdot \frac{i^2}{\delta^2}
\]  

(1)

2.2. The leakage analysis model
In labyrinth compressor, the labyrinth contains two parts, one part is a labyrinth seal between the piston and cylinder, the other is a labyrinth packing between the piston rod and seal. The two parts of the sealing principle is the same. When leaking gas flow within the labyrinth channel, its axial flow speed is greater than the circumferential speed along ring groove. As a result, the circumferential flow’s influence on the leakage gas can be neglected.

According to the labyrinth symmetric structure, this paper established a two-dimensional labyrinth leakage flow field analysis model by using FLUENT software as shown in figure 4. Due to the numerous model of labyrinth chamber, each chamber will produce eddy, in order to guarantee the accuracy of the calculation results, this paper USES the (RNG) \( k - \varepsilon \) turbulence model as given in equation 2. This model consider turbulent eddies and medium viscous force in the standard model of energy dissipation equation \( k - \varepsilon \), improve the calculation accuracy.

In the process of calculation, the finite volume method is adopted to discrete calculation equation, and mass conservation, momentum conservation equation and energy conservation equation using second order format.
Figure 4. The finite element model.

\[
\begin{align*}
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k \mu_i)}{\partial x_i} &= \frac{\partial}{\partial x_i} \left[ \frac{\partial k}{\partial x_i} \right] + G_k + G_{\rho \varepsilon} - Y_{\text{st}} + S_k \\
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon \mu_i)}{\partial x_i} &= \frac{\partial}{\partial x_i} \left[ \frac{\partial \mu_i}{\partial x_i} \right] + C_{1e} \frac{\varepsilon}{k} (G_k + C_3 \varepsilon) - C_{2e} \frac{\varepsilon^2}{k} - R_e + S_e
\end{align*}
\]  

(2)

3. Results and discussion

At present, the mainly method to analyze the electromagnetic field is finite element method, which basic idea is discrete the model calculation area fist, then joint variation principle and piece-wise interpolation method to calculate maxwell's equations of each discrete area boundary conditions. In this article, we use the software ANSOFT to analyze the electromagnetic field of radial electromagnetic coil. To simplify the calculation, this paper ignores the magnetic flux leakage and built two-dimensional finite element model of electromagnetic coil according to the established model symmetry, which is shown in figure 5. Figure 6 shows the electromagnetic coil magnetic field lines distribution.

Figure 5. The finite element model of radial electromagnetic coil.
In order to improve the dynamic characteristics of electromagnetic centering control system, this article introduce the variable speed into control system and take variable speed as the intermediate variable design the multivariable nonlinear decoupling feedback control strategy. Form the current, speed, displacement of three closed loop control system as shown in figure 7. In order to further test the electromagnetic centering control system reliability, we set up a test bench. We tested the current loop, speed loop and displacement loop of control system to make sure the correctness of the mathematical model. First of all, 1A was given to current loop and recorded the output current waveform, then compare with the actual result. The result shows in figure 8. Experiment and simulation results of overshoot amount are around 16% and adjust time is about 8 ms. There steady-state value both reached the expected ones and fit better. As shown in figure 9, after applying external disturbances on the controlled object, the given speed change and decay over time until to reach steady state due to the changes of radial displacement. In the whole process, the actual speed was controlled by displacement’s difference, and always can be in accordance with the given speed. The figure 10 shows that the experiment and simulation results of the displacement of controlled object fit well under the action of external force.

Figure 6. The distribution of magnetic characteristics.

Figure 7. The simulation model of electromagnetic guiding system.
Based on the dynamic mesh technique and regarded the eccentric trajectory as the boundary conditions of piston motion, this paper analyzed the leak amount change of the fourth column piston before and after the centering. The curve of the leakage before and after the electromagnetic center under the different pressure ratio is shown in figure 11. The leakage reduced 1.8 times after
applying electromagnetic centering. On the premise of applying electromagnetic centering, the leakage ratio of 0.1 mm clearance is relatively reduced more than 80% compared with 0.3 mm clearance.

![Image](image.png)

**Figure 11.** The leakage before and after centering

4. Conclusion

In a labyrinth piston compressor, the non-contact labyrinth seal is adopted between piston and cylinder mirror, which cause large clearance and serious leakage. The electromagnetic levitation technology was used to realize concentric centering between the piston and cylinder. And the traditional cantilever structure for the piston centering was transform into the simple support structure by using the through-piston rod. Established the three closed loop centering control system of current, speed and displacement and mathematical simulation model of electromagnetic centering control system. The experimental and simulated results showed that the electromagnetic centering control system can realize coaxial centering of the piston and cylinder. Fluent software analysis was used to study the electromagnetic control affects on the quantity of leaking. The results showed that by using electromagnetic centering technology and decreasing clearance between in cylinder wall and piston seal, the internal leakage of labyrinth reciprocating compressor can be reduced significantly and volumetric efficiency improved greatly.

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