Simulation and Experiment Study on Dynamic Characteristic of Reed Valve of Reciprocating Compressor Based on Fluid-Structure Interaction Model

Yanbin Wang, Bei Guo, Kai Ma, Yuhang Zhou,
School of Energy and Power Engineering, Xi’an Jiaotong University, Xi’an 710049, China;
Email: wanyanbin@stu.xjtu.edu.cn

Abstract. The working process of the suction valve with complex shape called “boqi” and the discharge valve with four arms were simulated by the three-dimensional fluid-structure interaction method in this paper. By setting the gap boundary condition between the valve and the valve plate, hanged the connection between the valve and the valve plate in the model, and the problem of flow area connectivity caused by the opening and closing of the valve was solved. It solved the mesh overlapped and distorted problem caused by the valve motion. According to the simulation, the results of valve’s dynamic characteristic and gas pressure were obtained. A valve displacement test bench of reciprocating compressor was built, and the valve motions under different rotational speed and different pressure ratio was tested. Comparing the simulation results with the experimental results, it shows that the three-dimensional fluid-structure interaction model can be used to simulate the interaction between the valve with complex shape and the compressor fluid field. From the simulation results, the pressure cloud map of the valve under different conditions was extracted. Finally, the method proposed in this paper was used to analyze the valve’s displacement, speed and stress.

1. Introduction
Reciprocating compressors are widely used in various fields, which are the core components of central air conditioners and commercial refrigerators. Reed valve is mainly used in small and medium-sized refrigeration compressors and air compressors. Valves are easy to fail, affecting economic benefits, so the research on valves is very important.

Early studies mostly used lumped parameter models to solve the valve motion problem. Tuhovcak, Hejcik and Jicha [1] analyze the heat transfer of the compressor working cavity, while Dutra and Deschamps [2] established a mathematical model of the compressor working process. The similarity between their models is that they both use a single degree of freedom model to predict the valve position. Papastergiou [3] uses the finite element method to solve the displacement of the reed valve, and the simulation and experiment results are consistent. Mistry [4] and Aigner [5-6] use the same method to model the flow field and valve separately, and obtain the pressure field of the working cavity and the movement of the suction and exhaust valves.

At present, scholars have realized the interaction of the valve and the flow field through the three-dimensional fluid-solid interaction method, and obtained the dynamic characteristics of the valve and the flow field distribution of the cylinder. Wang, Guo, and He [7] used a three-dimensional
fluid-solid interaction model to study the effects of speed and valve parameters of a refrigerator compressor on the delayed closing and flutter of the valve, and got the characteristic speed of the reed valve. Zhao, Jia, and Wen [8] studied the double-acting reciprocating compressor, and accurately obtained the relationship between pressure pulsation and valve movement. Silva and Deschamps [9] predicted the gas leakage of the reed valve of a small reciprocating compressor used in household refrigeration when the seal is not complete. This model takes into account the viscous friction, viscous flow state and compressibility of the refrigerant. Song, Wu and Li [10] studied the failure of the whole machine due to the damage of the suction valve and exhaust valve in the automobile air-conditioning compressor. Tan, Pan, Feng [11] and others have studied rolling piston compressors. The p-V diagram measured by experiments verifies the accuracy of the fluid-structure interaction model. Yu, Tan, and Ren [12] tested the p-θ diagram in the experiment to verify the accuracy of the model. Ba [13] used ADINA software to perform fluid-solid interaction simulations on the compressor valve, analyzed the dynamic characteristics of the valve and the thermal process of the compressor, and studied the influence of the thickness of the valve and the crankshaft speed on the movement of the valve;

This paper uses ADINA software to numerically simulate the working process of the complicated type Boqi suction valve and the four-arm strip exhaust valve in the reciprocating compressor based on the three-dimensional fluid-structure interaction method, and build an experimental bench for real-time acquisition of suction valve displacement to verify the simulation results. Obtain the dynamic characteristic curve of displacement, speed and stress of the suction valve.

2. Physical model and meshing
The research object of this article is a reciprocating air compressor, the two cylinders of the compressor are distributed in a "V" shape. Only one of the cylinders is selected for research. The main dimensions of this cylinder and the intake and exhaust valve groups are shown in Table 1.

| Item                      | Value  | Item                      | Value  |
|---------------------------|--------|---------------------------|--------|
| Cylinder diameter /mm     | 90     | Piston stroke /mm         | 60     |
| Link length /mm           | 170    | Crankshaft rotation radius /mm | 30     |
| Suction valve thickness /mm | 0.4   | Exhaust valve thickness /mm | 0.4   |
| Suction orifice diameter /mm | 5     | Exhaust orifice diameter /mm | 5     |

The suction valve is a Boqi type reed valve and the exhaust valve is a four arm strip reed valve. The root of the suction valve is pressed between the valve plate and the cylinder, which is simplified as a fixed part. The suction and exhaust valve lift limiter is shown in Figure 1. The suction valve lift limiter is a groove in the cylinder. Use a crescent-shaped plane instead in the model. Both the suction valve and the exhaust valve are made of 60CrMnA.

![Figure 1. Suction and exhaust valve lift limiter diagram](image-url)
When dividing the grid, first divide into blocks, then set the nodes, and finally generate the grid. In order to ensure that the mesh can maintain high quality after deformation, the flow field model is divided into 3D-8 node element meshes. The rigid surface of the suction valve plate, suction lift limiter, exhaust valve plate and exhaust lift limiter adopt 2D-4 nodes. The suction valve and the exhaust valve adopt a 3D-27 node grid. The grid division diagram is shown in Figure 2.

![Meshing diagram of flow field](image)

![Meshing diagram of lift limiter and valve plate](image)

![Meshing diagram of suction valve](image)

![Meshing diagram of exhaust valve](image)

**Figure 2.** Finite element model

3. **Solve the governing equations**

3.1 **Flow field governing equation**

Mass conservation equation:

\[
\frac{\partial \rho}{\partial t} + \text{div}(\rho \mathbf{u}) = 0
\]

(1)

Where \( \rho \) is Fluid density, \( t \) is time, \( \mathbf{u} \) is Fluid velocity vector, \( \mathbf{u} = (u_x, u_y, u_z) \).

Momentum conservation equation:

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \text{div}(\rho \mathbf{u} \otimes \mathbf{u} + \rho \mathbf{I}) = \rho \mathbf{F}
\]

(2)

Energy conservation equation:

\[
\frac{\partial (\rho e + \frac{1}{2} \rho \mathbf{u}^2)}{\partial t} + \text{div}(\rho e + \frac{1}{2} \rho \mathbf{u}^2 + \rho)\mathbf{u} = \rho \mathbf{F} \cdot \mathbf{u}
\]

(3)

3.2 **Structural control equations**

The governing equation expression of the structure is:

\[
M \ddot{\mathbf{U}} + C \dot{\mathbf{U}} + K \mathbf{U} = \mathbf{R} - \mathbf{F}
\]

(4)

Where \( M \) is Quality matrix, \( \dot{\mathbf{U}} \) is Acceleration vector , \( C \) is Damping matrix, \( \dot{\mathbf{U}} \) is Velocity vector, \( K \) is Stiffness matrix, \( \mathbf{U} \) is Displacement matrix , \( \mathbf{R} \) is External force vector, \( \mathbf{F} \) is Unit internal force.

When simulating the process of the gas valve colliding with the lift limiter and the valve plate, the contact boundary conditions are set on each contact surface, and the contact boundary is expressed as:
Where $g$ is Distance between two contact surfaces, $\xi$ is Normal contact pressure.

### 3.3 Fluid-solid interaction interface equation

The Euler (EULER) description method and the Lagrange (Lagrange) description method were used respectively in the flow field and the structure field. In the fluid-solid interaction calculation, if the structure field produces a large displacement, the difference between the two description methods will cause the fluid field and the structure field to separate at the originally coincident node on the fluid-structure interaction interface. In order to solve this problem, in the fluid-structure interaction calculation, the flow field adopts the Arbitrary Lagrangian-Eulerian coordinate system (Arbitrary Lagrangian-Eulerian, ALE). Displacement coordination and force balance can be expressed as:

\[ d_f = d_s \]  \hspace{1cm} \text{(6)}

\[ n \cdot \tau_f = n \cdot \tau_s \]  \hspace{1cm} \text{(7)}

Where $d_f$ is Fluid displacement vector, $d_s$ is Displacement vector of structure, $\tau_f$ is Fluid stress vector, $\tau_s$ is Structural stress vector.

### 4. Boundary conditions

#### 4.1 Gap boundary

In the expansion process and compression process, the compressor cylinder and other parts are not connected, but in the suction process and the exhaust process are connected, so in a working process of the compressor, the topological structure of the flow field will constantly change. Gap boundary conditions can effectively solve this problem. When using this boundary, a small gap needs to be reserved, and the Gap boundary is set in this gap flow field. In this paper, the capitalized Gap represents a special boundary condition in the model.

There are three ways to control the opening and closing of Gap: average pressure difference, time function and size of Gap. The third one is similar to the working process of the compressor valve, so this article adopts the third method: the Gap is controlled by the size of the grid. Extend the suction orifice to form a cylindrical surface, and the part in the clearance between the valve and the valve plate is the Gap boundary; In the same way, there is also a Gap boundary around the exhaust orifice.

#### 4.2 Import and export boundary conditions and initial conditions

The boundary conditions imposed on the fluid field in this paper are shown in Figure 3. It is necessary to set boundary conditions at the inlet of the intake cavity and the outlet of the exhaust cavity.

![Figure 3. Boundary condition setting of flow field model](image-url)
In the calculation, the time when the piston reaches the top dead center position is zero, and the suction valve is closed at this time. As the gas expands, the suction valve will gradually open. Therefore, with the Gap on the suction side as the boundary, two relatively independent fluid regions are formed respectively, the area on the side of the suction port is called EXTERNAL, and the other part is called INTERNAL. Set the initial conditions respectively.

4.3 Setting of boundary conditions of solid field
The boundary condition setting of the solid field includes fluid-structure interaction boundary, displacement fully constrained boundary and contact boundary, the fluid-structure interaction boundary corresponds to the fluid-structure interaction boundary in the flow field. The full restraint of the suction valve is set at the root of the valve where the actual valve installation screw. The contact boundary includes two contact pairs, as shown in Figure 4. The exhaust valve is similar to the suction valve.

![Figure 4. Boundary condition setting of suction valve](image)

5. Reciprocating compressor suction valve displacement test experiment

5.1 Experimental setup
The entire system is mainly composed of a reciprocating air compressor, an air storage tank, a frequency converter and a test system. The test system consists of eddy current displacement sensor, Hall sensor and data acquisition system. The experimental compressor is V-0.67/8 reciprocating air compressor. The motor’s rated speed is 980 r/min and rated power is 5.5 kW. Intake pressure of the compressor is 0.1 MPa and rated exhaust pressure is 0.8 MPa. Change the degree of valve opening to adjust the pressure of the gas tank, and start data collection when the pressure stabilizes at the set working condition. The eddy current displacement sensor is used to measure the valve displacement, and the installation position is shown in Figure 5.

![Figure 5. Schematic diagram of the installation position of the eddy current displacement sensor](image)

5.2 Verification of fluid-structure coupling model
This paper sets up 9 working conditions: the pressure ratio is 3, 4 and 5; the speed is 408r-min⁻¹, 603r-min⁻¹ and 980r-min⁻¹. The trend of valve movement curve in simulation and experiment is basically the same. The maximum displacement, opening angle and closing angle of the valve are shown in Table 2. The maximum error of the maximum displacement, opening angle and closing angle is within the allowable range.
Table 2. Main thermal parameters of compressor

| Pressure ratio | Rotating speed/ \( \text{r/min} \) | Maximum displacement /mm | Error /mm | Opening angle /° | Error /° | Close corner /° | Error /° |
|----------------|-----------------------------------|--------------------------|-----------|------------------|----------|-----------------|----------|
|                | simulation                        | experiment               | simulation| experiment       | simulation| experiment       | simulation|
| 3              | 408                               | 2.00                     | 0.00      | 29.4             | -0.2     | 181.2           | -3.1     |
|                | 603                               | 2.11                     | 0.11      | 30.4             | 3.1      | 193.7           | -0.8     |
|                | 980                               | 2.10                     | 0.06      | 32.3             | 2.8      | 201.7           | -3.9     |
| 4              | 408                               | 2.03                     | 0.05      | 34.9             | -3.0     | 180.5           | -4.2     |
|                | 603                               | 2.10                     | 0.14      | 37.5             | -0.7     | 192.1           | -2.5     |
|                | 980                               | 2.1                      | 0.12      | 38.2             | -3.1     | 204.0           | 3.3      |
| 5              | 408                               | 2.05                     | 0.09      | 39.8             | -1.0     | 180.5           | -4.3     |
|                | 603                               | 2.10                     | 0.14      | 42.3             | -0.2     | 192.7           | -1.2     |
|                | 980                               | 2.10                     | -0.09     | 44.0             | 2.7      | 209.3           | 1.1      |

In summary, the three-dimensional fluid-solid interaction model established in this paper is effective, and it is suitable for the interaction analysis of the complex shape valve and the surrounding flow field in the compressor.

6. Research on Dynamic Characteristics of Reed Valve of Reciprocating Compressor Based on Fluid-Structure Interaction

6.1 Pressure analysis of the suction valve surface

The pressure difference controls the movement of the valve, so the pressure distribution on the upper and lower surfaces of the valve is extracted from the simulation results. The cylinder side is regarded as the lower surface, and the cylinder head side is regarded as the upper surface. Here only shows the pressure distribution when the speed is 980\( \text{r-min}^{-1} \) and the pressure ratio is 3. Five stages are taken for analysis, the result shown in Figure 6.

![Figure 6](image-url)  
Figure 6. Cloud diagram of pressure distribution on the upper and lower surfaces of the valve  
It can be seen that the pressure distribution of the suction valve lower surface is very uniform in all time periods. During the opening phase, an obvious low pressure area appears on the upper
surface of the valve, of which the pressure is less than the intake pressure. This is because the clearance on the upper surface of the valve is narrow and the air flow is complicated, so the pressure distribution is uneven.

In order to better understand the relationship between the pressure on the upper surface of the valve and the speed, the pressure distribution along the width and length of the valve when the valve is half-open at different speeds is studied. Set up three pressure monitoring coordinate axes and six displacement monitoring points as shown in Figure 7. Points 3, 4, 5, and 6 are located in the center of the suction valve holes. Point 2 is located at the test area of the eddy current displacement sensor above. Point 1 is located at the head of valve. Axis X1 and X2 are horizontal axis, passing through points 3, 4 and 5, 6. Axis Y is the vertical axis, which is the symmetry axis of the valve.

![Figure 7. Selection of monitoring coordinate axes and points of suction valve](image)

Figure 7. Selection of monitoring coordinate axes and points of suction valve

Figure 8 shows the pressure distribution in the X and Y direction of the valve. Due to similar trends, only a few cases are selected as examples. It can be seen that with the increase of speed, the pressure distribution in different areas becomes more uneven, and the pressure valley value is obviously reduced, while the pressure peak value do not have much difference. With the increase of the speed, the pressure of the valve along the length direction becomes smaller.

![Figure 8. Pressure graph at different speeds along the coordinate direction](image)

(a) X1 pressure ratio 3  (b) X2 pressure ratio 4  (c) X1 pressure ratio 5  (d) Y pressure ratio 3

6.2 Analysis of dynamic characterisists of suction valve

6.2.1Displacement

The valve motion curve is an important factor to analyze whether the valve structure is reasonable. Through the displacement curve, the valve opening angle, closing angle and other information can be obtained. Therefore, this article analyzes the movement law of the suction valve at different speeds and pressure ratios.

By monitoring the points 3, 4, 5, and 6, the motion curves of the symmetric points are coincident. It shows that there is no side deviation of the suction valve during the working process. Therefore, only monitoring points 1 and 2 are analyzed.

The deformation curve is shown in Figure 9. It can be seen that the valve reaches the maximum lift in a very short time after opening, and then the head of the valve is close to the lift limiter. With the increase of speed, the opening angle does not change much, the closing angle increases
obviously, the valve closes later, and the working cycle becomes longer. Because the intake pressure loss increases with the increase of the speed, the pressure difference between the two sides of the valve is greater when the speed is high, and the cylinder pressure needs to be further increased, so the valve closes later.

In order to understand the movement of other parts after the valve head is close to the lift limiter, extract the displacement curve of point 2 at different pressure ratios and speeds. After the valve hits the limiter and closes tightly, the monitoring point 2 begins to vibrate, and as the speed increases, the frequency of reciprocating motion becomes smaller. And as the speed increases, the opening angle and closing angle increase, the oscillation frequency decreases.

![Graphs of valve movement](image)

**Figure 9.** The movement of monitoring point 1 and 2 of the suction valve changes with the speed in same pressure ratio

### 6.2.2 Velocity

The relationship between the movement speed and the angle of rotation at different speeds of detection point 1 and 2 is shown in Figure 10. It can be seen that in the figure (a) the speed of the suction valve suddenly increases and then drops to zero quickly. Until the valve falls back, there will be a rebound, and the rebound speed is less than 0.5 m/s, so when the valve is closed, the impulse is not large, and then the speed becomes 0 again. This is a working cycle of the suction valve.

![Graphs of speed change](image)

**Figure 10.** Speed change graph of monitoring point 1 and point 2

According to the above analysis of the pressure distribution on the surface of the suction valve, it can be seen that during the opening phase of the suction valve, a low pressure area is generated on the upper surface, and the pressure in the low pressure area is less than the inlet pressure of the
valve port. With the change of speed, the minimum pressure of the low pressure zone changes, and the area of the low pressure zone changes, so the acceleration of the valve movement changes. It can be seen that in the figure (b) the speed of monitoring point 2 initially increases suddenly, then decreases and starts to increase in the reverse direction, but the maximum reverse speed is small. The change of speed then shows a simple harmonic vibration with a small amplitude. In a cycle, the valve swings up and down many times, indicating that the alternating stress at the root of the intake valve changes rapidly.

6.2.3 Stress
From the above analysis, it can be seen that the valve vibrates during operation, it will generate cyclic stress and cause fatigue damage, so it is very necessary to perform stress analysis on the valve. In this paper, the movement process of four working periods are selected for stress analysis when the pressure ratio is 3 and the speed is 480\text{ min}^{-1}, and the stress distribution cloud diagram as shown in Figure 11.

Figure 11. Stress distribution diagram of suction valve
It can be seen from Figure 11 that the maximum stress of the valve is mainly concentrated at the root of the valve. Figure 12 shows the change of the maximum stress at the root of the suction valve with the crankshaft angle. It can be seen that the maximum stress occurs at an angle of 40 degrees, which has the same trend as the displacement diagram. The maximum stress at the root changes continuously with the vibration of the monitoring point 2. When the displacement of monitoring point 2 is the maximum, the root stress is the maximum.

Figure 12. The maximum stress at the root of the suction valve varies with the angle of rotation

7. Conclusions
In this paper, ADINA software is used to simulate the reciprocating compressor air valve working process by fluid-structure interaction method, and obtain the motion curve. Compared with the experiment results, and get the following conclusions:
1) In three-dimensional fluid-solid interaction problems, changing the properties of the fluid connection surface dynamically by setting the gap boundary conditions can solve the flow area connection problem caused by the opening and closing of the valve. It can control the coupling boundary and the flow field grid near it to solve the problem of excessive deformation and overlap of the flow field grid caused by the movement of the valve;
2) The movement law curve of the suction valve obtained by the three-dimensional fluid-solid interaction model is basically consistent with the movement law of the suction valve measured by the experiment. It shows that the fluid-solid interaction model can accurately simulate the interaction law between the reed valve and the compressor flow field, and is suitable for valve models with complex shapes;

3) In this paper the dynamic characteristics of the compressor valve is analyzed. The results show that the head speed of the suction valve increases suddenly after the valve is opened, and then it will keep close to the lift limiter, the rest of the part will vibrate. With the increase of speed, the vibration frequency and opening angle change little, but the closing angle increases; As the pressure ratio increases, the valve opening angle increases significantly. In the working process of the suction valve, the maximum stress is concentrated at the root of the valve, and the change trend of the maximum stress and displacement of the root is basically the same.

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