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ABSTRACT

Discharge valve is very critical component in rotary compressor, and it is a reed valve which consists of valve seat, valve slice and retainer. The motion characteristics of valve slice greatly influence the flowing loss and life of valve. The paper presents a mathematical model to simulate thermodynamic process and motion of the valve simultaneously. Based on the thin-plate theory, the finite element model of the valve slice is built up, and the iso-parametric element of eight nodes is adopted which has good adaptability to shape of the valve slice. The valve seat and retainer are taken as stationary boundary conditions. The gas flow through the suction and discharge ports, and the thermodynamics of real refrigerant have been taken into consideration. The Runge-Kutta method and the Newmark method have been taken to solve the equations.
In this paper, the influence of the discharge valve with same valve slice and different retainer on the compressor's efficiency and reed valve's dynamic stress has been analyzed. The analysis results matches with the experimental results. The proper retainer can be designed to optimize the efficiency and reliability of the valve.

1. INTRODUCTION

Rotary compressor has been widely used in room air-conditioners. Discharge valve is a critical component, which consists of valve seat, valve slice and retainer, as shown in Figure 1. Figure 2 shows the geometry of the valve slice.

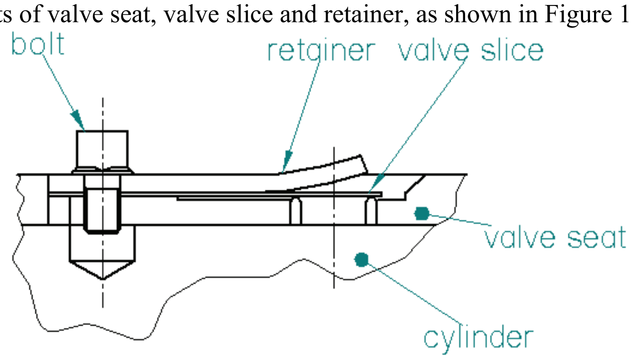

Figure 1: Schematic diagram of discharge valve

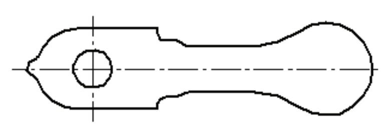

Figure 2: Schematic diagram of valve slice

Ensuring the high efficiency and reliability of the compressor has become more and more important with increasing requirements of the customer and policy. The discharge loss influences the efficiency a lot, as we all know, through increasing the lift of the retainer, the efficiency will increase much, but the reliability will decrease. So mostly, there is a conflict between high efficiency and high reliability. Reliability has been influenced by a lot of factors, such as material, manufacturing, abnormal operating condition, and design. The effect of profile of retainer upon the fatigue life has been studied by Jan-Shiew, 1992. Based on the commercial finite element method software ANSYS, the natural frequencies and static stresses of valves with different retainers have been analyzed. The research found that small defect on profile of retainer due to manufacturing carelessness may result in valve fracture (Jan-Shiew, 1992). Influences of valve on pressure pulsation in suction manifold and discharge muffler have also been studied respectively (Jeong 2006; Yikai Yuan, 2006).

In this paper, based on the dynamic analysis of the valve, the influences of valve on performance and reliability have been conducted.

2. NUMERICAL MODEL

The finite element method has been conducted to simulate the motional behavior of the valve. The efficiency and the stress distribution of the valve slice while opening have been calculated by coupling the thermodynamic analysis of the practical refrigerant and the dynamic analysis of the valve.

2.1 Dynamic analysis of the valve

Based on the thin-plate theory, the finite element model of the valve slice is built up, and the iso-parametric element of eight nodes is adopted which has good adaptability to shape of the valve slice, as shown in Figure 3. The shape function can be obtained as Equation (1). The schematic diagram of the finite element discretization of the valve is shown in Figure 4.

$$\begin{cases} \varphi_i(\xi,\eta)=1/4(1+\xi_i\xi)(1+\eta_i\eta)(\xi_i\xi+\eta_i\eta-1) & i=1,2,3,4 \\ \varphi_i(\xi,\eta)=1/2(1-\xi^2)(1+\eta_i\eta) & i=5,7 \\ \varphi_i(\xi,\eta)=1/2(1-\eta^2)(1+\xi_i\xi) & i=6,8 \end{cases} \tag{1}$$

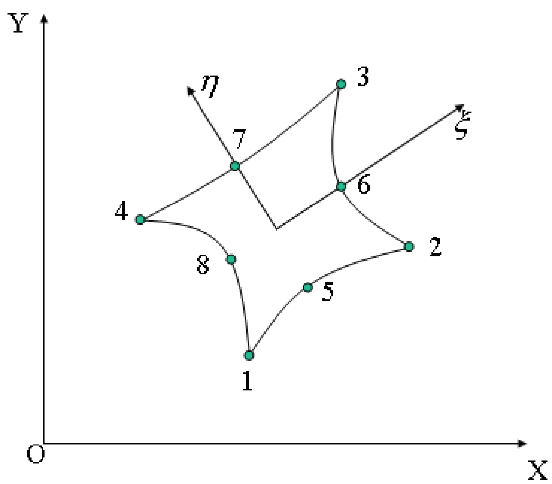

Figure 3: The iso-parametric element of eight nodes

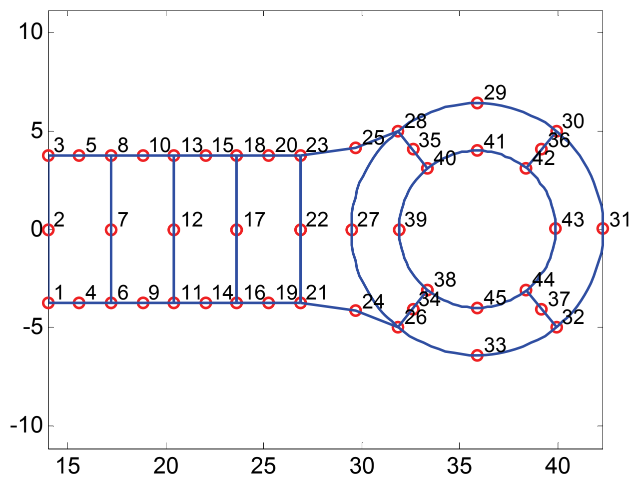

Figure 4: Finite element discretization of the valve slice

Displacement situation of any point on the thin-plate can be described as vector $\{w,\theta_x,\theta_y\}^T$; therefore, displacement in X, Y, Z directions can be expressed as Equation (2). The motion equation of the valve slice can be deduced as Equation (3)

$$u=z\theta_y, v=-z\theta_x, w=w(x,y) \tag{2}$$

$$[M]\{\ddot{q}\}+[K]\{q\}=\{F_{gas}(\theta)\} \tag{3}$$

Where $[M]$ is the mass matrix, $[K]$ is the stiffness matrix, $\{q\}$ is vector of displacement of node, $\{q\}=\{w,\theta_x,\theta_y\}^T$, $F_{gas}(\theta)$ is gas force acting on the valve slice, θ is the rotational angle of the shaft.

The valve seat and retainer have been treated as static boundary of the motion of the valve. The curve of the retainer consists of a straight line and an arc as shown in Figure 5, and its lift $H(x)$ can be described as Equation (4) with its origin at start of the arc. After the valve hits the valve seat or retainer with a certain velocity, it will come back in opposite direction with less velocity. As shown in Equation (5), instantaneous displacement of the node is lift of the retainer, the rebound velocity is the impacting velocity multiplied by rebound coefficient.

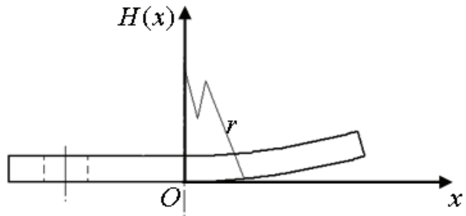

Figure 5: Valve retainer

$$H(x) = r - \sqrt{r^2 - x^2} \tag{4}$$

$$\begin{cases} h = H(x) \\ v = -C_R \bullet v \end{cases} \tag{5}$$

Where, r is radius of the arc, C_R is rebound coefficient.

The motion equation of valve slice has been solved by Newmark method, and then coupled with the thermodynamic process by Runge-Kutta method through the relationship between motion of the valve and discharge mass. The Newmark method is expressed as following.

Assume,

$$\{\ddot{q}\} = \{\ddot{q}_t\} + 2\alpha\left(\{\ddot{q}_{t+\Delta t}\} - \{\ddot{q}_t\}\right) \tag{6}$$

Integrating Equation (6) yields,

$$\{q_{t+\Delta t}\} = \{q_t\} + \Delta t\{\dot{q}_t\} + \left[\left(\frac{1}{2} - \alpha\right)\{\ddot{q}_t\} + \alpha\{\ddot{q}_{t+\Delta t}\}\right]\Delta t^2 \tag{7}$$

We can solve,

$$\{\ddot{q}_{t+\Delta t}\} = a_1\left(\{q_{t+\Delta t}\} - \{q_t\}\right) + a_2\{\dot{q}_t\} + a_3\{\ddot{q}_t\} \tag{8}$$

Where,

$$a_1 = \frac{1}{\alpha \Delta t^2} \qquad a_2 = -\frac{1}{\alpha \Delta t} \qquad a_3 = -\left(\frac{1}{2\alpha} - 1\right)$$

Substituting Equation (8) into Equation (6), we can obtain,

$$\left[\bar{K}\right]\{q_{t+\Delta t}\} = \left\{F_{gas}\left(t + \Delta t\right)\right\} + \left\{\bar{F}\left(t + \Delta t\right)\right\} \tag{9}$$

Where,

$$\left[\bar{K}\right] = a_1[M] + [K]$$

$$\left\{\bar{F}\right\} = [M]\left(a_1\{q_t\} - a_2\{\dot{q}_t\} - a_3\{\ddot{q}_t\}\right)$$

2.2 Thermodynamic analysis

The Runge-Kutta method has been used to solve the thermodynamic equations. The discharge mass flow equations have a relation with the motion equation of the valve slice.

2.2.1 Energy equation.

Governing equations of the thermodynamic model have been derived from mass and energy conservation equations with the equation of state for real refrigerant R22. The energy equation with respect to rotational angle is shown as Equation (10).

$$\frac{dT}{d\theta} = \frac{1}{c_v m}\{\frac{1}{\omega_s}(\sum_i \dot{Q}_i + \sum_i h_i \dot{m}_i) - [h - v(\frac{\partial h}{\partial v})_T + v^2(\frac{\partial P}{\partial v})_T]\frac{dm}{d\theta} - [(\frac{\partial h}{\partial v})_T - v(\frac{\partial P}{\partial v})_T]\frac{dV}{d\theta}\} \tag{10}$$

Where $\dot{m}_i$ and $\dot{Q}_i$ represent the mass flow rate and heat flow rate entering or exiting the governing volume, respectively.

2.2.2 Discharge mass flow equations.

Discharge process has been taken as one-dimensional compressible flow through nozzle. The mass flow rate with respect to rotational angle can be described as

$$\frac{dm}{d\theta} = \alpha_d A_v u / \omega \tag{11}$$

Where, area of valve clearance $A_v = \pi D_d h_v$, D_d is the diameter of the discharge port, h_v is lift of the valve,

Velocity of flow $u = \sqrt{\frac{2k}{k-1}\frac{P_1}{v_1}\left(\gamma^{\frac{2}{k}} - \gamma^{\frac{k+1}{k}}\right)}$,

$$\gamma = \begin{cases} \frac{P_2}{P_1}, & \frac{P_2}{P_1} \geq \gamma_{cr;} \\ \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}, & \frac{P_2}{P_1} < \gamma_{cr.} \end{cases} \qquad \gamma_{cr} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}.$$

3. ANALYSIS OF THE VALVE FRACTURE

3.1 Phenomenon of the Valve Fracture

In order to improve the performance of the compressor, the valve's lift has been increased from 1.97mm to 2.8mm through changing the retainer. After operating for average time of one month, the compressors were locked or couldn't build the pressure difference between suction and discharge. Through disassembling these compressors for inspection, we found valve fracture occurred as shown in Figure 6. The factors that influence the reliability of the valve are including material, manufacture procedure, assembling, abnormal working condition, design and so on. Through improving manufacture procedure and optimizing the shape of retainer, the problem has been solved. In this paper we only theoretically analyze the motional behavior of the valve, and optimize the retainer's shape to meet with the requirements of the performance and reliability.

Figure 6: Valve fracture

3.2 The Theoretical Analysis of Valve Fracture

Before using the model to solve practical problems, we must ensure the validity of the program. Therefore, during developing the program, we compared the static deformation and natural frequency of the valve slice with commercial software ANSYS to verify the model.

Regarding to the valve fracture, the influence of the discharge valve with same valve slice and different retainer on the compressor's efficiency and reed valve's dynamic stress has been analyzed. Different shapes of the retainers and calculation results have been presented in Table 1. In case 1, the mass production retainer with lift of 1.97mm was analyzed; in case 2, the retainer which caused the valve fracture was also analyzed; and in case 3, the latest optimized retainer has obtained. The calculation results show that the retainer in case 3 not only improves COP, but also decreases the maximum dynamic stress of the valve slice.

.Table 1: Geometrical parameter of the retainers and calculation results

Retainer	Case 1	Case 2	Case 3
Valve's lift at center of the discharge port /mm	1.97	2.8	2.8
Radius of arc /mm	85	60.55	85.224
Length of the straight line /mm	14	14	10.534
Maximum stress /MPa	132.7723	156.1707	141.5621
Theoretical COP	3.100815	3.133214	3.145800

Variation of gas pressure in governing volume is shown in Figure 7, the over-compression loss in case 1 is maximum, the discharge pressure pulsation in case 2 is maximum because of flutter of the valve slice. Variation of valve's lift at center of the discharge port, which is shown in Figure 8, represents that the flutter of the valve slice in case 2 is most serious, maybe that is the reason to cause the valve fracture.

Variation of the maximum stress of valve slice is shown in Figure 9, the stress value in case 2 is maximum and the amplitude of fluctuating stress in case 2 is also the maximum. That confirms that possibility of fatigue failure in case 2 is largest. Figure 10 represents at which nodes of valve slice the maximum stress occurs; through that we can find which points are most vulnerable to failure. The numbering nodes are shown in Figure 4. Based on the results, we can find the maximum stress concentration on node 26 or node 20, the maximum stress at node 26 only appears instantly when the valve slice reaches the maximum deformation, the maximum stress at node 20 appears for a long time. So the most probable position for fatigue failure is at node 20, the neck of the valve slice, just as practical fracture shown in Figure 6. Stress distribution when the maximum stress occurred in case 2 is shown in Figure 11.

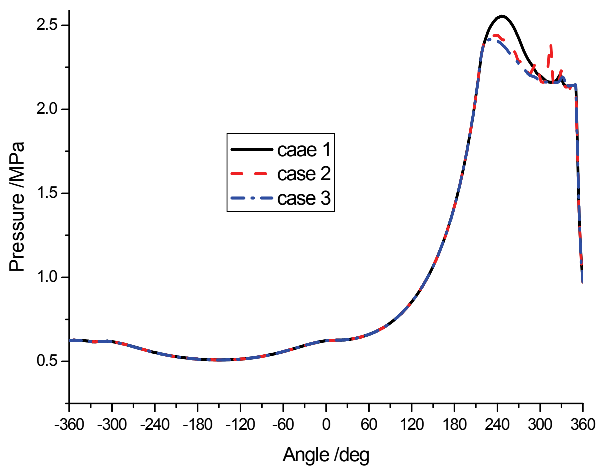

Figure 7: Variation of gas pressure

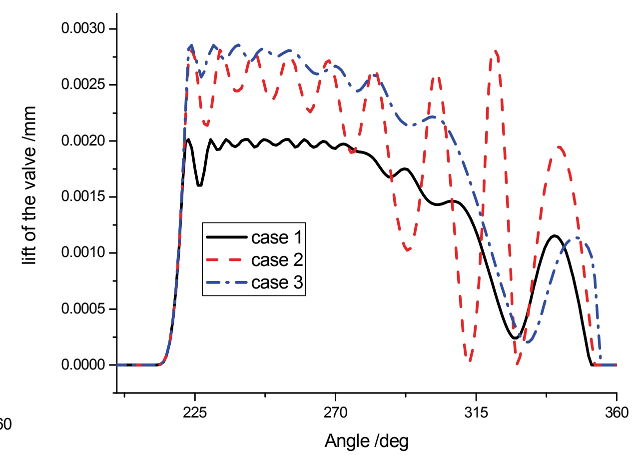

Figure 8: Variation of valve's lift at center of the discharge port

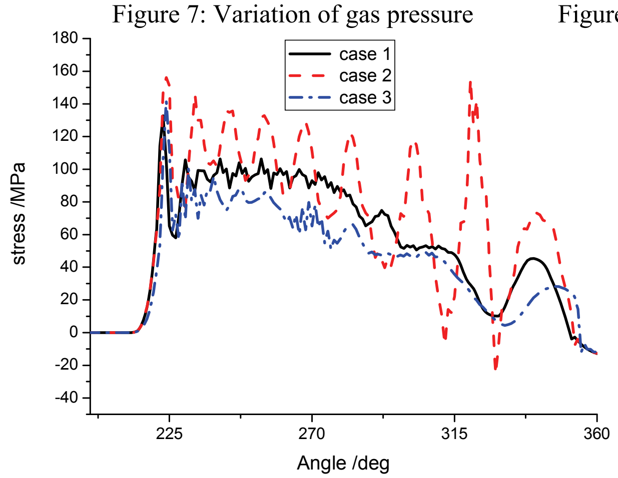

Figure 9: Variation of maximum stress

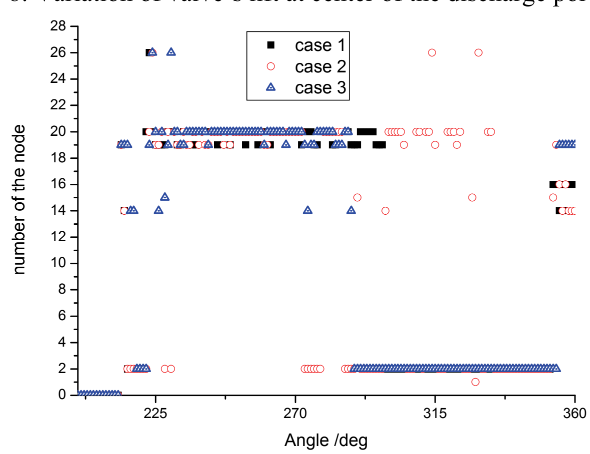

Figure 10: Node numbers corresponding maximum stress

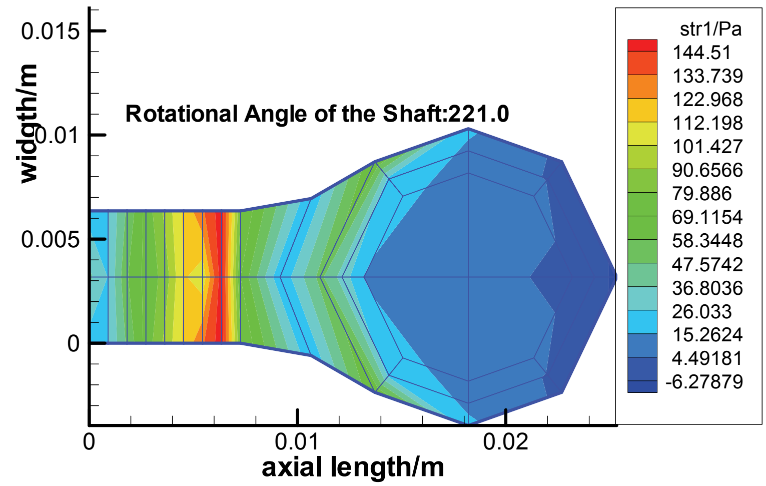

Figure 11: stress distribution when the maximum stress occurred in case 2

4. CONCLUSIONS

In this paper, the valve slice's motion behavior and stress variation have been studied though dynamic analysis of the valve slices. Properly designing the valve slice and retainer can improve the performance and ensure the reliability. We only demonstrate influence of the different retainer on the system in this paper; actually, we can also analyze the influence of the shape, thickness, stiffness (material) on performance and reliability of the compressor. The valve slice's motion behavior not only influences the performance and reliablility of the compressor, but also influences the discharge pressure pulsation to excite the noise. That is our next research.

NOMENCLATURE

A_v	Area of valve clearance	T	Temperature
A_s	Area of suction port	ω	Rotational angular velocity
α_s	Coefficient of suction flow	h	Valve's lift or enthalpy
α_d	Coefficient of discharge flow	P	Pressure
θ	Rotational angle of shaft	D_d	Diameter of the discharge port

REFERENCES

Danqing Wu, Jingtong Cong, 1993, Mathematical Simulation and Design of Reed Valve of Compressor, China Machine Press.

Jeong I.P, Nasir B., Douglas E.A., 2006, Development of a Two-Dimensional Finite Element Model of a Suction Valve for Reduction of Pressure Pulsation in the Suction Manifold of a Multi-Cylinder Automotive Compressor, *International Compressor Engineering Conference at Purdue*, C029

Yikai Yuan, Jianhua Wu, 2006, Investigation on the Pressure Pulsation in the Discharge Muffler of Rotary Compressors. *International Compressor Engineering Conference at Purdue*, C030

Jan-Shiew Ho, Rei-Yian Chen, 1992, the Effect of Profile of Backing Plate Upon the Fatigue Life of a Cantilever Discharge Valve Reed, *International Compressor Engineering Conference at Purdue*: p. 927-933.

Jianhua Wu, 1998, Study on Performance and Dynamics of Inverter Controlled Rotary Compressor, *Doctor's Thesis*.