Force and Stress Analysis of Connecting Rod bushing

Qiangbing Dong, Zheng Liang

***Abstract*—As an important moving part of the compressor, connecting rod bushing is subjected complex alternating pitman force. Connecting rod bushing is connected directly to crosshead pin, pitman force is exerted on the bushing in the form of reaction. The mathematical calculation model of pitman force is worked out by analysing the gas force at different crank angle. By building three-dimensional model of moving parts with SolidWorks and then SolidWorks Motion is used to carry out the dynamic simulation, finally kinetic parameters of simulation model is obtained. Comparing the simulation results with the resolution function analytical calculation results, function formula of pitman force was verified. And then carry out a finite element simulation of connecting rod small end though ANSYS Workbench, it is concluded that the connecting rod bushing stress decreases with the increase of clearance at the allowed range of the fit clearance—connecting rod bushing with the crosshead pin.**

***Index Terms*—compressor, connecting rod bushing, pitman force, gas force, dynamic simulation, stress**

I. Introduction

Reciprocating compressor, as a kind of universal equipment, already is widely used in petroleum, chemical, and other fields. At present, the reciprocating compressor is widely used in petroleum and natural gas compressor. The moving part of reciprocating compressor is mainly composed of the crankshaft, connecting rod component, crosshead and piston component. As one of the important parts of the compressor, the main function of connecting rod component is converting the rotary motion of the crankshaft into a reciprocating motion of the piston. The connecting rod bushing is subjected to a periodic pitman force during the motion process, and the pitman force changes with the change of the crank angle. Because of the importance and complexity of connecting rod bushing in compressor parts, it is important to analyze the force of it.

In this paper, by analyzing the pressure variation of the shaft side and cover side of the cylinder, a deep research on the change of the whole cycle is launched, like compression—exhaust—expansion—suction—compression. Using SolidWorks to build the 3D model of the moving parts of the compressor, and then carry on the dynamic simulation though SolidWorks Motion. Compared the connecting rod force in feature points of function analysis and simulation results, the error is very small. It verifies the correctness of the mechanical calculation model of the connecting rod bushing. And then carry out a finite element simulation of connecting rod small end though ANSYS Workbench, to study the change of the connecting rod bushing stress, in the case of the different fit clearances of the connecting rod bushing and crosshead pin.

Qiangbing Dong (1990-), male, master graduate student, the main research direction is the oil and gas compressors.

Zheng Liang (1960-), male, Professor, the main research direction is design and manufacturing of oil and gas equipment.

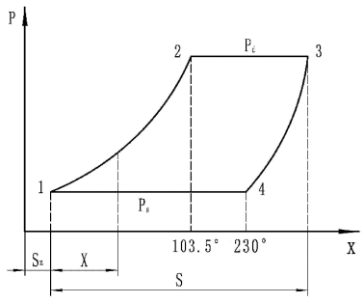
II. Force Analysis

During the reciprocation of compressor, the connecting rod big end is connected with crank pin, and the small end with crosshead pin. The connecting rod bushing is played a role as hinge joint. The big end and crankshaft do the rotary motion, and the small do reciprocating motion with the piston component together. During this process, the connecting rod is subjected to an alternating load, such as tension, compression, etc. The pitman force acts on the connecting rod bushing in the form of a reaction force.

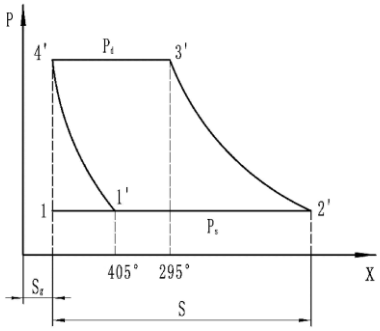
The connecting rod bushing is mainly subjected to the inertia force I generated by the reciprocating movement of the piston component and the gas force F_g transferred by crosshead pin. The friction force produced between relative motion surfaces can be neglected compared to the former two. The magnitude and direction of these forces are periodical, therefore, the connecting rod is subjected to an alternating compression and tensile load [1]-[4]. And here analyze the moving process of the piston from the bottom dead center to top dead center. When the piston is at the bottom dead center, the displacement of crosshead and the angle of crankshaft are both zero. The connecting rod stretched direction is the positive direction of the coordinate axis.

A. Gas Force Calculation

The gas force is algebraic sum from the products of gas pressure on both sides of the piston and the effective area of piston. The formula for the gas force calculation is shown as equation (1) [1-6]. While the gas pressure inside the cylinder changes with the movement of the piston, also the crank angle varies. The pressure indicating diagram of the cylinder is showed in Fig.1.



(a) Pressure indicating diagram of shaft side



(b) Pressure indicating diagram of cover side

Fig.1. Pressure indicating diagram

$$F_g = \frac{\pi}{4}[P_z(D^2 - d^2) - P_g D^2] \quad (1).$$

It shows from Fig.1 that, during the process of starting from the bottom dead center of the piston to the top dead center, the shaft side of cylinder exhibits a state of compression – Exhaust – expansion – suction – compression (1–2–3–4–1), while the cover side is suction – compression – Exhaust – expansion – suction. The main parameters of compressor are showed in Table 1.

Tab.1. The main parameters of compressor

Project	Value
Compression cylinder diameter D (mm)	120
Piston rod diameter d (mm)	38.1
Equivalent length of shaft side clearance S_z (mm)	9
Equivalent length of cover side clearance S_g (mm)	10
Intake pressure P_s (MPa)	0.6
Exhaust pressure P_d (MPa)	2.1
Compression index n	1.36

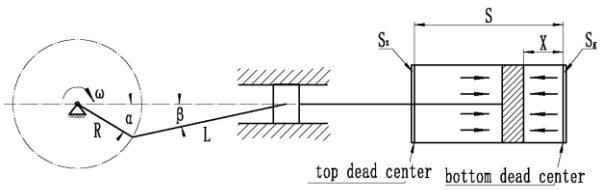


Fig.2. Schematic diagram of compressor moving parts

The follow formula can be gained from Figure 2:

$$\begin{cases} X = (R + L) - (R\cos\alpha + L\cos\beta) \\ R\cdot\sin\alpha = L\cdot\sin\beta \end{cases} \quad (2).$$

Then it can be calculated that:

$$X = R[(1-\cos\alpha) + \frac{(1-\sqrt{1-\lambda^2\sin^2\alpha})}{\lambda}]$$

Then $\sqrt{1-\lambda^2\sin^2\alpha}$ can be further calculated though Taylor expansion and higher-order are neglected, there is:

$$\sqrt{1-\lambda^2\sin^2\alpha} = 1 - \frac{\lambda^2\sin^2\alpha}{2} - \frac{\lambda^4\sin^4\alpha}{4} - \cdots\cdots$$

And then $\sqrt{1-\lambda^2\sin^2\alpha} = 1 - \frac{\lambda^2\sin^2\alpha}{2}$, so the displacement of piston is:

$$X = R[(1-\cos\alpha) + \frac{\lambda}{4}(1-\cos 2\alpha)] \quad (3).$$

The piston acceleration is achieved by getting the second-order derivative with respect to time,

$$a = \omega^2 R(\cos\alpha + \lambda\cos 2\alpha) \quad (4).$$

The function diagram of piston displacement and acceleration is showed in Fig.3 and Fig.4 respectively.

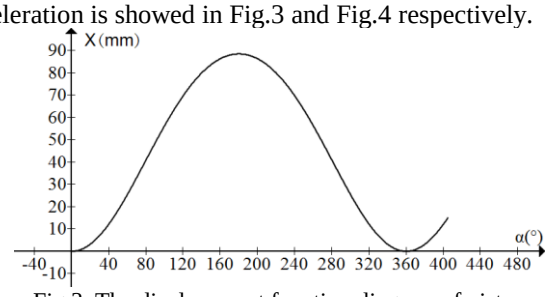


Fig.3. The displacement function diagram of piston

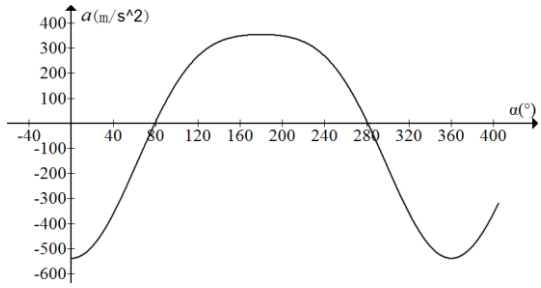


Fig.4. The acceleration function diagram of piston

When the piston from the bottom center to the top center movement, the shaft side compression and cover side intake. Cover-side gas pressure is $P_g = P_s = 0.6$ MPa. Shaft side gas pressure is calculated as Eq. (5) [1]:

$$P_z = \left(\frac{S + S_z}{S + S_z - X}\right)^n P_s \quad (5).$$

It can be known from Fig. 1, when the pressure reaches point 2, the compression process of shaft side is completed. At this time, $P_z = P_d = 2.1$ MPa, the piston displacement can be obtained, $X = 58.93$ mm. By the same, the crank angle can be concluded from Fig. 3, $\alpha = 103.5°$.

During this process, the gas force is F_g (N):

$$F_g = \frac{3110332.7619}{(44.25\cos\alpha + 2.268\cos 2\alpha + 51.382)^{1.36}} - 6782.4$$

$$(0 \le \alpha < 103.5°)$$

Shaft side gas enters the process of exhaust after finishing the compression, and cover side is suction process. While at 180°of crank Angle, the exhaust process of shaft side is over. During this process, $P_z = P_d = 2.1$ MPa, $P_g = P_s = 0.6$ MPa, the gas force is F_g (N):

$$F_g = 14563.02 \ (103.5° \le \alpha < 180°)$$

When the piston from the top center to the bottom center movement, shaft side gas begins to expand and cover side begins to compress. At this time, shaft side gas pressure is calculated as Eq. (6) [1]:

$$P_z = \left(\frac{S_z}{S + S_z - X}\right)^n P_d \quad (6).$$

It can be known from Fig. 1(a), when pressure is varying from point 3 to point 4, the shaft side gas complete expansion process. $P_z = P_s = 0.6$ MPa, the piston displacement can be obtained, $X = 75.29$ mm. The crank Angle at this time can be obtained from Fig. 3, $\alpha = 230°$.

Cover-side gas pressure is calculated as follow [1]:

$$P_g = \left(\frac{S+S_g}{S_g+X}\right)^n P_s \qquad (7).$$

It can be known from Fig. 1(b), when pressure is varying from point 3´to point 4´, the cover side gas complete compression process, $P_g = P_d = 2.1\,\text{MPa}$. Similarly, the displacement of the piston can be drawn, $X = 29.368\,\text{mm}$. The crank Angle at this time can be obtained from Fig. 3, $\alpha = 295°$.

During this process, the gas force is F_g (N) :

$$F_g = \frac{449531.64}{(44.25\cos\alpha + 2.268\cos 2\alpha + 51.382)^{1.36}} - \frac{3506310.3672}{(-44.25\cos\alpha - 2.268\cos 2\alpha + 56.518)^{1.36}} \quad (180° \le \alpha < 230°)$$

Similarly, it can be calculated that, at the processes of the shaft side suction – cover side compression, shaft side suction – cover side exhaust and shaft side compression – cover side expansion, the gas force is respectively F_g (N) :

$$F_g = 6098.69169 - \frac{3494993.246}{(-44.25\cos\alpha - 2.268\cos 2\alpha + 56.518)^{1.36}}$$

$$(230° \le \alpha < 295°)$$

$$F_g = -17639.70831 \ (295° \le \alpha < 360°)$$

$$F_g = \frac{3110332.7619}{(44.25\cos\alpha + 2.268\cos 2\alpha + 51.382)^{1.36}} - \frac{543815.31888}{(-44.25\cos\alpha - 2.268\cos 2\alpha + 56.518)^{1.36}} \quad (360° \le \alpha \le 405°)$$

When the crank Angle is greater than 405°, shaft side gas is compressed and cover side discharged, the gas force varies as the processes described above. The function diagram of gas force with the crank angle between 0 and 405° is showed in Fig. 5.

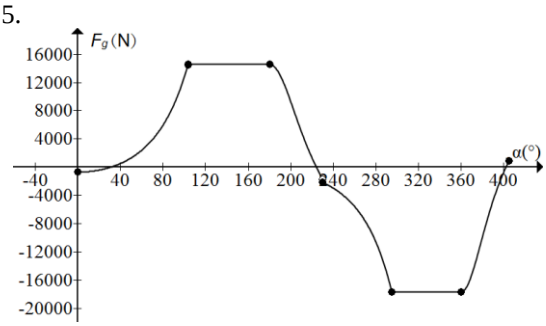


Fig.5. Function diagram of gas force

B. Reciprocating inertia force calculation

The piston and crosshead component are both under reciprocating motion, it can be approximated that, the quality of these components are concentrated in the hinge of the crosshead pin and connecting rod bushing. The reciprocating mass of unit (the sum of the piston and crosshead component) is, $m_p = 20.557\,\text{kg}$.

The reciprocating inertia force generated by the reciprocating mass is showed as Eq. (8) [1]-[5]:

$$\begin{cases} I = m_p a \\ a = R\omega^2(\cos\alpha + \lambda\cos 2\alpha) \end{cases} \qquad (8).$$

When the piston is moving from the bottom center to the top center, the inertia force makes compression trend to connecting rod, so its direction is negative. Then it can obtain $I = -9184(\cos\alpha + 0.205\cos 2\alpha)$. The function diagram of reciprocating inertia force is showed as Fig.7.

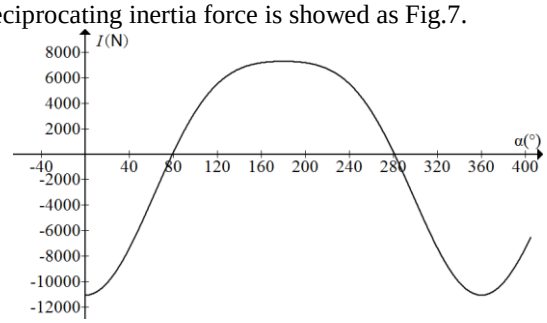


Fig.7. Function diagram of reciprocating inertia force

C. Pitman force calculation

Ignoring the friction generated by the surface of the relative motion. The analysis diagram of pitman force is showed in figure 8, and the comprehensive piston and pitman force are respectively as bellow [1]-[5]:

$$\begin{cases} F_p = F_g + I \\ F_l = F_p / \cos\beta = F_p \dfrac{1}{\sqrt{1-\lambda^2\sin^2\alpha}} \end{cases} \qquad (9).$$

According to the above description and Eq. (11), it can be obtained that the function diagram of pitman force is showed as Fig.9.

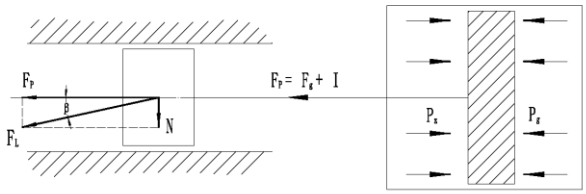


Fig.8. Analysis diagram of pitman force

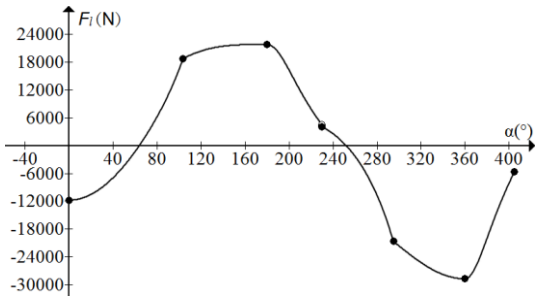


Fig.9. Function diagram of pitman force

It can be known from Fig.9, the pitman force is the largest when crank angle is 360°, it is $F_l = 28706\,\text{N}$, the direction is negative.

III. Dynamics Simulation

Establishing the 3D assembly model of compressor cylinder moving parts (crankshaft, connecting rod component, crosshead and piston component) and adding material properties of the various parts. SolidWorks own material library can easily realize the material distribution of the model. The 3D model of compressor moving parts is showed in figure 10.

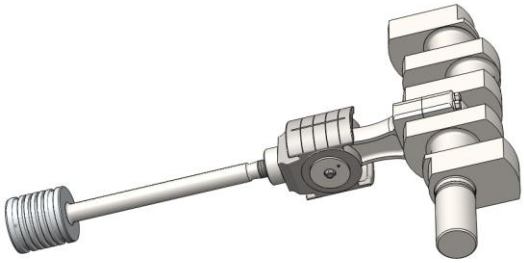


Fig.10. 3D model of compressor moving parts

SolidWorks Motion can transform constraint relation defined between parts assembly to corresponding kinematic pair. Material properties of parts will be also reflected in SolidWorks Motion [2]-[3]. Though motor command, add the power end of the crankshaft rotational speed in a clockwise direction for 960r/min. The piston movement cycle is 0.0625s, through keyboard code attribute set simulation time about 0.07s (crank angle 0-405°). Add the downward gravity which is also perpendicular to the piston movement direction. In the process of the piston motion, just add the role of gas force. The reciprocating inertia force will be applied automatically to the appropriate agency, according to the crankshaft speed applied and the quality distribution of each component calculated by SolidWorks Motion. Ignore the friction force produced between relative motion surfaces when the simulation in progress.

After SolidWorks Motion simulation, the reaction graphic in the X-component (cylinder axis direction) and Y-component (direction perpendicular to the cylinder axis) are both obtained at the hinge of the connecting rod bushing and crosshead pin. They are showed in figure 12 and 13 respectively.

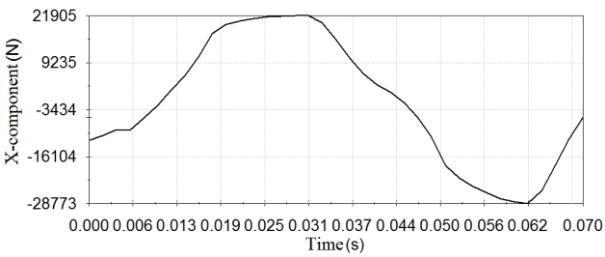


Fig.12. Reaction graphic in the X-component

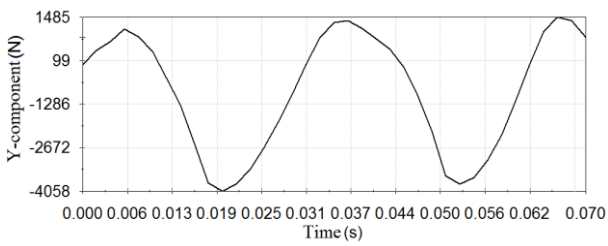


Fig.13. Reaction graphic in the Y-component

Output the reaction simulation in CSV form, the size of resultant force – pitman force can be obtained according to the reaction components in X and Y directions. At the time of 0.062s while the crank angle is 360°, the maximum pitman force is 28773N with negative direction. While according to Fig.9 the function diagram of pitman force, it is 28706N. The error obtained between the simulation results and function analytical results is as small as 0.233%.

IV. Finite Element Analysis

Use SolidWorks to establish 3D solid model of the connecting rod small end, showed in figure 14. Then import the model ANSYS Workbench and do a finite element analysis. To study the relationship with the fit clearance and its stress while the connecting rod bushing at the maximum pitman force. The material characteristics of connecting rod, connecting rod bushing and crosshead pin showed in Table 2.

Table.2. Material properties of model

Project	Connecting rod	Connecting Rod bushing	Crosshead pin
Material	42CrMo	QSn7-0.2	20Cr
Density ρ (kg/m³)	7850	8780	7830
Elastic Modulus E (Pa)	2.12E+11	1.1 E+11	2.07E+11
Poisson ratio μ	0.28	0.33	0.254
Yield strength δ_S (Pa)	9.3E+8	4.8E+8	5.4E+8
Ultimate strength δ_b (Pa)	1.08 E+9	5.8E+8	8.35E+8

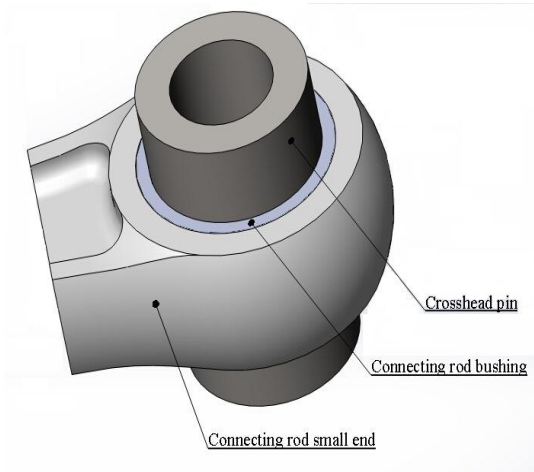


Fig.14. 3D model of connecting rod small end

It is an interference fit between the connecting rod and connecting rod bushing, and the magnitude of interference is 0.08mm. Apply the maximum pitman force to the crosshead pin as bearing load, the size is 28700N. To analyze the stress of connecting rod bushing, the fit clearance of crosshead pin and connecting rod bushing is in the range of 0.04-0.1mm. After analysis by ANSYS Workbench, the variation graph of connecting rod bushing stress is showed in figure 15. The stress nephograms at the clearance of 0.04mm and 0.1mm are respectively showed as figure 16 and 17.

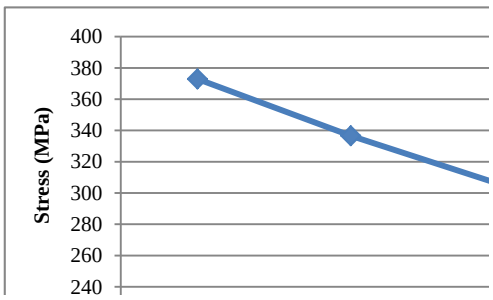


Fig.15. Stress of connecting rod bushing

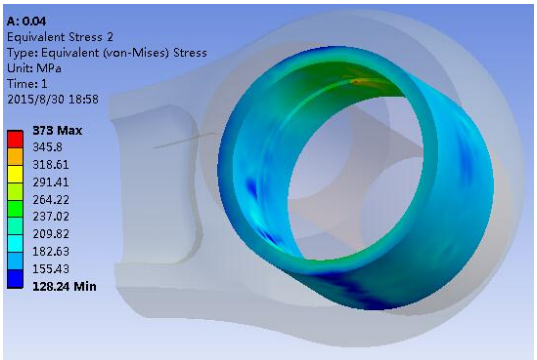


Fig.16. Stress nephogram at 0.04mm

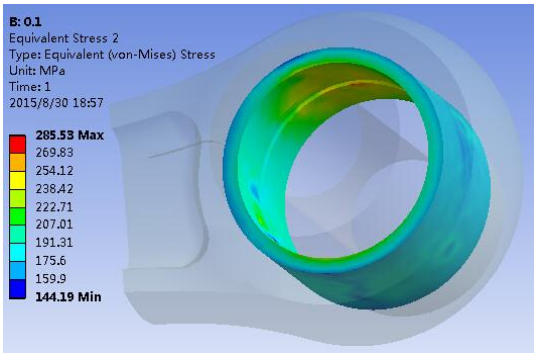


Fig.17. Stress nephogram at 0.1mm

It can be seen from Fig.15, the stress of connecting rod bushing decreases with the increase of clearance when the fit clearance is in the range of 0.04-0.1mm.

V. Conclusion

In this paper, by calculating the indicator diagram of cylinder gas pressure in different crank angle, the mathematical calculation model of pitman force is obtained. By building three-dimensional model of moving parts with SolidWorks and then SolidWorks Motion is used to carry out the dynamic simulation. It can clearly know that the mathematical calculation model and simulation results are consistent, and also it proves the correctness of theoretical formula. The dynamic simulation of SolidWorks Motion also provides a new method of compressor dynamic calculation. Meanwhile, the mathematical calculation model of pitman force also provides an accurate calculation basis and data foundation for the structural optimization and finite element analysis of compressor. And then carry out a finite element simulation of connecting rod small end though ANSYS Workbench, it can easily draw the conclusion that, the stress of connecting rod bushing decreases with the increase of clearance in the design range of fit clearance.

Reference

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