Finite Element Analysis for the High Pressure Rotary Cylinder Block

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Abstract—As a pneumatic actuator, high pressure rotary cylinder has been successfully used in some ships, which can provide large torque output and is small and easy to install. The finite element method is used to calculate the cylinder block of high pressure rotary cylinder, and the stress and deformation of the cylinder block are analyzed by using the real stress-strain curve of metal materials. The distribution of stress and deformation is obtained. Moreover, the influence of 1 \textasciitilde 7MPa gas pressure on stress and deformation of the cylinder block is investigated. The maximum stress and deformation of the cylinder block under different pressure loads are obtained. The analysis results provide a basis for the design and operation of high pressure rotary cylinder.

1. INTRODUCTION

Rotary cylinder (also known as swing cylinder) is a pneumatic actuator that uses compressed gas to drive the output shaft to make reciprocating rotary motion and output torque within a certain angle range. As a pneumatic actuator, rotary cylinder has been successfully used in some ships, such as the opening and closing of pneumatic valves or doors or windows. Many rotating cylinders on ships need to be able to provide large enough torque output, and need to be small and easy to install. Most of the general rotary cylinders on the market are low-pressure cylinders with a pressure lower than 1MPa, which cannot meet the above requirements. Therefore, a high-pressure rotating cylinder is required. The loads borne by the high-pressure rotating cylinder during operation mainly include gas pressure, rotating torque, installation preload, inertia force and so on. Under these loads, the cylinder will produce greater stress and deformation. Reasonable material and structural design shall be adopted to meet the operation requirements. However, the stress and deformation in the cylinder are difficult to obtain through the test.
The traditional design method adopts empirical design, which is difficult to meet the accuracy requirements of modern design. With the gradual maturity of three-dimensional modeling software, finite element calculation software and numerical calculation software, the use of finite element method can study the strength, stiffness and stability of complex structures with low cost. It is a widely used calculation method in industrial design [1-5]. Many scholars have used the finite element method to analyze the parts of the engine cylinder [6,7]. Zhao et al. [6] have carried out the finite element analysis on the deformation of the cylinder inner circle of the rotary compressor and verified it by experimental simulation calculation. Xiao Qiang et al. [7] carried out finite element analysis on the stress and deformation of the cylinder piston of reciprocating compressor, which provided a reference basis for the structural design of the piston. The real stress-strain curves of many materials are not linear [8-9], but many mathematicians do not consider these, which will lead to deviation in the analysis results.

In this paper, the finite element method is used to calculate the cylinder block of high-pressure rotating cylinder, and the stress and deformation of the cylinder block are analyzed. Using the real stress-strain curve of materials, the effects of gas pressure on the stress and deformation of cylinder block are investigated.

2. FINITE ELEMENT MODEL
The three-dimensional modeling, mesh generation, material distribution, load and constraint definition of the cylinder block of high-pressure rotating cylinder are carried out, and the finite element analysis and research are used.

2.1 Structural model
The physical drawing of the cylinder and the three-dimensional model drawing of the cylinder are shown in Figure 1. The overall shape of the cylinder is a cuboid, and the two air inlet holes are strengthened by small cuboid blocks outside, as shown in Figure 1 (b). The interior is a cylindrical cavity, one air inlet is directly connected with the internal cavity, and the other air inlet is connected with the internal cavity at both ends through the internal channel, as shown in Fig. 1 (c). In Figure 1 (b), four large bolt holes for fixing the cylinder block and four bolt holes for fixing the gear shaft are designed on the cylinder block. Due to the irregular external structure in the cylinder body, tetrahedral grid is adopted, and the grid division is shown in Figure 1 (d).
2.2 Materials
The high-pressure rotating cylinder on the ship is required to work normally in the environment of salt fog and mold. In this paper, 304 stainless steel is adopted.

Figure 2 shows the stress-strain curve of Austenitic 304 stainless steel (06Cr19Ni10), which shows typical nonlinear characteristics. When the stress is greater than 100 MPa, it shows anisotropy, that is, the stress-strain curves of transverse and longitudinal, tensile and compressive are different. The proportional limit of 304 stainless steel is low. The yield limit of 304 stainless steel is given as 206 MPa in the domestic mechanical design and calculation manual [10]. In the design of pressure vessels, GB 150.1-2011 [11] stipulates that the safety factor is 1.5 and the allowable stress is about 137 MPa. In some codes [12,13], the allowable stress of 304 stainless steel in non-pressure vessels is between 210 MPa and 240 MPa, and the specific value is determined according to the material thickness.

![Figure 2](image-url)

Figure 2. True stress-strain curve of austenitic 304 stainless steel [8]

The main parameters of 304 stainless steel (06Cr19Ni10) is shown in Table I. In the finite element analysis, the real stress-strain curve data of materials in Figure 2 are used and fitted.

| Material Science | Density g/cm³ | Poisson’s ratio | Yield limit MPa | Tensile strength MPa |
|------------------|---------------|----------------|-----------------|--------------------|
| 304              | 7.93          | 0.29           | 206             | 520                |
2.3 Load
The load borne by the high-pressure rotating cylinder during operation mainly includes the following parts:

(1) The cylinder block is under the pressure of compressed gas, and all places under the pressure of gas (including the inner cavity, air inlet and internal channel of the cylinder) define the pressure load;

(2) The cylinder block is subjected to the rotating torque of the output shaft, and the maximum output torque load is defined in the cylinder block;

(3) The cylinder block is fixed with four bolts, and the four bolt holes are subject to the installation preload of the bolts and are defined as constraint sets.

The gas pressure, rotating torque, installation preload load and constraint set distribution defined on the cylinder block are shown in Figure 3.

3. Results and Discussion

3.1 Stress and deformation distribution
It is defined that the pressure load of compressed gas is 4 MPa, the torque load inside the cylinder block is 580 N•m, and the installation preload of four bolt holes by bolts is 100 N • m respectively. The stress distribution of the cylinder block obtained by analysis is shown in Figure 4. As can be seen from the stress distribution contour of the cylinder block in Figure 4 (a), the maximum concentrated stress obtained from the analysis is 118.7 MPa, which occurs at the upper left and lower right bolt holes of the cylinder block as shown in Figure 4 (a). These two bolt holes are the constraint set of the cylinder block. During the operation of the cylinder, the rotating torque of the cylinder block is the largest, and the wall thickness is smaller than the surrounding, Stress concentration is caused by gas pressure and installation preload. Figure 4 (b) shows the cross-sectional stress distribution nephogram of the air hole channel in the cylinder block. It can be seen that the maximum stress in the air hole channel in the cylinder block is 65.31 MPa, which is the place with the maximum stress except the four bolt holes, about half of the maximum stress in the cylinder block. The stress distribution on the inner surface of the cylinder is shown in Figure 4 (c), with the maximum value of 58.2 MPa, which occurs on the left and right sides of the output shaft hole shown in Figure 4 (c), and gradually decreases outward respectively.
Figure 4. Stress distribution of cylinder block

Figure 5 shows the analysis results of the deformation distribution of the cylinder block. Figure 5 (a) shows the contour line of the deformation distribution, and figure 5 (b) shows the cloud diagram of the deformation distribution of the cylinder block in section. Combined with figure 5 (a) and figure 5 (b), it can be seen that the maximum deformation of the cylinder block is about 0.01 mm, the deformation is very small, occurs in the center opposite to the air inlet of the cylinder block, and gradually decreases from the center to the periphery. This is because the interior of the cylinder block is a cylindrical cavity, the wall thickness at the horizontal center line of the surface (view (a) in Figure 5) is the thinnest, and the moment at the center of the surface is the largest.
3.2 Effect of gas pressure
In order to investigate the influence of different pressure loads on the stress and deformation of the rotating cylinder block. The pressure load, rotating torque load and installation preload load defined on the cylinder block are shown in Table II. Under the action of different compressed gas pressures, the rotating torque in the cylinder body is equal to the maximum output torque of the cylinder under this pressure. The installation preload of the four bolt holes is fixed at 100 N•M.

**TABLE II. LOADS DEFINED ON THE CYLINDER BLOCK**

| Pressure load MPa | Rotating torque load N·m | Installation preload load N·m |
|------------------|--------------------------|-----------------------------|
| 1                | 145                      | 100                         |
| 2                | 290                      | 100                         |
| 3                | 435                      | 100                         |
| 4                | 580                      | 100                         |
| 5                | 725                      | 100                         |
| 6                | 870                      | 100                         |
| 7                | 1015                     | 100                         |

Fig. 6 shows the changes of the maximum stress and deformation of the cylinder block under different pressure loads. It can be seen that the maximum stress and deformation of the cylinder block are directly proportional to the pressure load. GB 150.1-2011[11] stipulates that the allowable stress of 304 stainless steel in pressure vessel design is 137 MPa, while the allowable stress of 304 stainless steel in non pressure vessel in international code is 210 ~ 240 MPa. When the air pressure is greater than 1 MPa, the cylinder block has exceeded 1 MPa•L, which belongs to pressure vessel. As can be seen from figure 8 (a), when the gas pressure is 5 MPa, 6 MPa and 7 MPa, the maximum concentrated stress on the cylinder block is 148.4 MPa, 178.8 MPa and 208.7 MPa respectively, which occurs at the fixed bolt hole, exceeding the allowable stress of 304 stainless steel in the design of pressure vessel by 137 MPa [11], but also less than the allowable stress of 304 stainless steel in non pressure vessel by 210 ~ 240 MPa [12,13]. Figure 7 shows the outline diagram of stress distribution of cylinder block under 7 MPa air pressure. It can be seen that the maximum stress except the bolt hole is 87.27 MPa, which occurs on the air hole channel inside the cylinder block, which is less than the allowable stress of 304 stainless steel in the design of pressure vessel 137 MPa [13], while the maximum stress at the bolt hole is 208.7 MPa, which is close to the allowable stress of 304 stainless steel in non pressure vessel 210 ~ 240 MPa. It indicates that the design limit has been reached. In conclusion, when 304 stainless steel is selected for the cylinder block of this design structure, the maximum gas pressure during cylinder operation is not allowed to exceed 7 MPa, and it is suitable to control it within 5 MPa [12,13].

![Graph a](image1.png)  ![Graph b](image2.png)

(a) Maximum stress  (b) Maximum deformation

Figure 6. Maximum stress and deformation of cylinder block under different pressures
Figure 7. Outline of stress distribution of cylinder block under 7 MPa air pressure

4. CONCLUSION
Through the finite element analysis of the stress and deformation of the high-pressure rotating cylinder block, the following conclusions are obtained.

(1) Under the action of gas pressure, rotating torque and installation preload, the maximum stress of the cylinder body is concentrated in the fixed bolt hole, followed by the air hole channel in the cylinder body. The maximum deformation of the cylinder block occurs in the center opposite to the air inlet of the cylinder block, and gradually decreases from the center to the periphery.

(2) When the cylinder body of this design structure is made of 304 stainless steel, the maximum gas pressure during cylinder operation shall not exceed 7 MPa, and it is better to control it within 5 MPa.

The analysis results of this paper provide a basis for the design and operation of high-pressure rotating cylinder.

REFERENCES
[1] GIRIUNAS K, SEZEN H, DUPAIX R B. Evaluation, modeling, and analysis of shipping container building structures[J]. Engineering Structures, 2012(43): 48–57.
[2] Jin S Y, Huang Z G, Shao Z K, et al. A Study on Rotary Expanding Process of Large-Diameter Hot-Rolled Seamless Gas Cylinder with Finite Element Analysis[J]. Advanced Materials Research, 2011, 320:45-51.
[3] Prati C, Tribst J, Piva A, et al. 3D Finite Element Analysis of Rotary Instruments in Root Canal Dentine with Different Elastic Moduli[J]. Applied Sciences, 2021, 11(6):2547.
[4] Chien P Y, Walsh L J, Peters O A. Finite element analysis of rotary nickel-titanium endodontic instruments: A critical review of the methodology[J]. European Journal of Oral Sciences, 2021.
[5] Chan H F, Collier G J, Parra-Robles J, et al. Finite element simulations of hyperpolarized gas DWI in micro-CT meshes of acinar airways: validating the cylinder and stretched exponential models of lung microstructural length scales[J]. Magnetic Resonance in Medicine, 2021, 86(1).
[6] ZHAO Xumin, CHEN Hui. Finite Element Analysis and Experimental Study for Bore Deformation of Rotary Compressor Cylinder[J]. Chinese Journal of Refrigeration Technology, 2015, 34(2): 73-76.
[7] XIAO Qiang, ZENG Yan, GUO Tian-xing. Finite Element Analysis for Stress and Deformation of Cylinder Piston of Reciprocating Compressor[J]. Compressor Technology, 2020, 282(4): 25-29.
[8] Rasmussen K J R, Burns T, Bezkorovainy P, et al. Numerical modelling of stainless steel plates in compression[J]. Journal of Constructional Steel Research, 2003, 59(11): 1345-1362.
[9] ZHU Haochuan, YAO Jian. Stress-strain model for stainless steel[J]. SPATIAL STRUCTURES, 2011(01):62-69.
[10] Wang Sanmin. Mechanical design calculation manual [M]. Beijing: Chemical Industry Press, 2009:36-36.
[11] Shou Binan. Interpretation of GB 150-2011 pressure vessels [M]. Xinhua press, 2012:37-41
[12] EN 1993-1-4. Eurocode 3: Design of steel Structures-Part 1.4: General Rules and Supplementary Rules for stainless steels[S]. European standards, CEN, 2006.
[13] SEI/ASCE 8-02. Specification for Cold-Formed Stainless Steel Structural Members[S]. American society of Civil Engineers, 2002.
[14] AS/NZS 4673. Cold-formed stainless steel structures[S]. Australian/New Zealand Standards, 2001.