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A Topology Optimization Design of Compressor Connecting Rod

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A Topology Optimization Design of Compressor Connecting Rod

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Abstract: To address the problems of unstable and noisy compressor operation caused by excessive mass of the connecting rod of reciprocating piston compressor, a multi-objective topology optimization algorithm based on the compromise planning method is used to optimize the design of the connecting rod by considering both dynamic low-order inherent frequency and stiffness, and a multi-objective function of joint stiffness and inherent frequency is proposed. The finite element model is established and the optimized model is revalidated. The analysis results show that the optimized connecting rod mass is reduced by 21.6%, the low-order inherent frequency is improved, and the material meets the requirements of strength and stiffness.

1.Introduction

The compressor connecting rod is an important part of the reciprocating piston compressor, whose task is to convert the rotational motion of the crankshaft into the reciprocating linear motion of the piston[1]. The connecting rod is always subjected to alternating tensile and compressive stresses that change in size and direction during operation. If the quality of the compressor connecting rod is too large, it will not only cause material waste, but also damage the balance of the crankshaft motion and cause excessive noise during compressor operation. Therefore, the performance and reliability of the connecting rod structure directly affects the smooth operation of the compressor.

At present, in the study of the reliability of connecting rod, many scholars have done relevant research, generally using the method of finite element analysis. Yan Shuai [2] used finite element analysis to optimize the structure topology of rocker arm structure, improve the mechanism stress strain and enhance the fatigue life. Based on the FEA software ABAQUS, Zhu Xinyao[3] et al. conducted statics analysis of the connecting rod based on finite element analysis software ABAQUS, and obtained the stress distribution cloud map and displacement cloud map under the worst compression conditions. On this basis, topology optimization of the connecting rod was carried out to reduce the quality of the connecting rod. Tan Meilan [4]et al. used the secondary development of ABAQUS software to obtain the fatigue calculation module of connecting rod, to realize the automatic loading of dynamic load, and to obtain the fatigue life of connecting rod based on the critical plane method. Zhang Yong[5]et al. softened the connecting rod and established a multidynamics model of the crank-slider mechanism, and found that the flexural multidynamics model was closer to the actual situation by comparing the multirigid model and the flexural multidynamics model. The above research is significant for the reliability study of connecting rod.

In this paper, the topology optimization method is used to redesign the compressor connecting rod, and the compromise planning method is used to define the static multi-state objective function, and the mean frequency method is used to define the dynamic vibration frequency objective function, and the model that satisfies both static stiffness and inherent frequency is obtained through optimization, which improves the overall performance of the connecting rod.

2.Multi-objective Topology Optimization Techniques and Theory

2.1.Multi-condition stiffness topology optimization model

The stiffness problem is often transformed into a problem of flexibility to solve in engineering. In the problem of multi-case strain energy minimum topology optimization, each load condition corresponds to the optimal topology, and in this paper there are two conditions corresponding to the objective function of two structural minimum strain energy, and in order to satisfy the results of different conditions at the same time, the multi-objective function is transformed into a single-objective topology optimization to solve it using the compromise planning method. The sub-objective function is regularized to combine several sub-objectives with different properties, and weights are added in front of each sub-objective according to the importance of each sub-objective in the design.

From the compromise programming method, the objective function for the topological optimization of static.

multi-condition stiffness can be obtained as:

$$\begin{cases} \mathrm{minC}(\rho) = \{\sum_{k=1}^{l} \omega_k [\frac{c_k(\rho)-c_k^{min}}{c_k^{max}-c_k^{min}}]^p\}^{\frac{1}{p}} \\ \mathrm{s.t} \quad \mathrm{v(x)/v_0} \le \mathrm{f} \end{cases} \tag{1}$$

Where: l is the total number of load conditions, ω_k is the weight coefficient of different conditions, $c_k(\rho)$ is the objective function of the Kth condition, c_k^{min}, c_k^{max} are the minimum and maximum values of flexibility of the kth condition objective function, v(x) is the volume function, x is the density of the design cell, v_0 is the original structure volume, f is the volume constraint, and p is the penalty factor.

2.2. Dynamic intrinsic frequency topology optimization objective function

The inherent frequency topology optimization model takes the maximum value of the inherent frequency of several lower orders as the objective function, while using the volume as the constraint, but when the inherent frequency of one order reaches the maximum, the inherent frequency of other orders may decrease, leading to the order order swapping with each other, which will make the objective function oscillate, so the average frequency formula is used to overcome the objective function oscillation problem.

$$\underset{x=(x_1,x_2,\ldots\ldots,x_n)}{max\ \Lambda(\rho)} = \lambda_0 + s\left(\sum_{i=1}^{f} \frac{\omega_i}{\lambda_i-\lambda_0}\right)^{-1} \tag{2}$$

Where: $\Lambda(\rho)$ is the average frequency function, $(x_1, x_2, \ldots\ldots, x_n)$ is the design variable, λ_0 is the given parameter to adjust the objective function, ω_i is the weight factor of the ith order eigenfrequency, f is the order, and λ_i is the ith order eigenfrequency.

2.3. Multi-order objective function considering multi-order intrinsic frequencies

Using the volume as the constraint, the objective function considering both the multi-objective stiffness and the maximum low-order intrinsic frequency, an algorithmic model based on the compromise planning method combined with the average frequency formula is used.

$$\mathrm{MinC(X)}=\{w^2 \sum_{k=1}^{n} w_k^q [\frac{C_K-C_K^{min}}{C_K^{max}-C_K^{min}}]^q + (1-w)^2 [\frac{\Lambda_{max}-\Lambda(x_e)}{\Lambda_{max}-\Lambda_{min}}]\}^{\frac{1}{q}} \tag{3}$$

Where: q is the penalty factor, w is the flexibility objective function weight coefficient, $(1-\mathrm{w})$ is the weight coefficient of the frequency objective function, Λ_{max}, Λ_{min} are the maximum and minimum values of the frequency objective function before and after topology optimization.

3. Working Condition and Load Calculation

3.1. Working load of connecting rod

The compressor connecting rod in operation is mainly subjected to the gas pressure brought by the piston, the inertia force generated when the crank connecting rod mechanism is in motion, and the frictional force generated between the relative moving surfaces. In addition, when the connecting rod is installed, the interference fit between the small end of the connecting rod and the bushing also causes the small end to generate the squeezing force from inside to outside.

The combined piston forces on the compressor are:

$$F_P = F_G + F_f + F_{IS} + F_{IR} \tag{4}$$

Where: F_G is the gas force, F_f is the combined friction force, F_{IS} is the reciprocating inertia force, F_{IR} is the rotational inertia force.

3.2. Structural parameters and force curves

Piston stroke: S=140mm, piston rod diameter: d=60mm, crankshaft speed: n=960r/min, crank radius: r=60mm, crank connecting rod ratio: $\lambda = 1/5$, connecting rod length: l=450, mechanical efficiency: $\eta = 0.87$. The measured force on the connecting rod in actual operation is shown in the Figure.1.

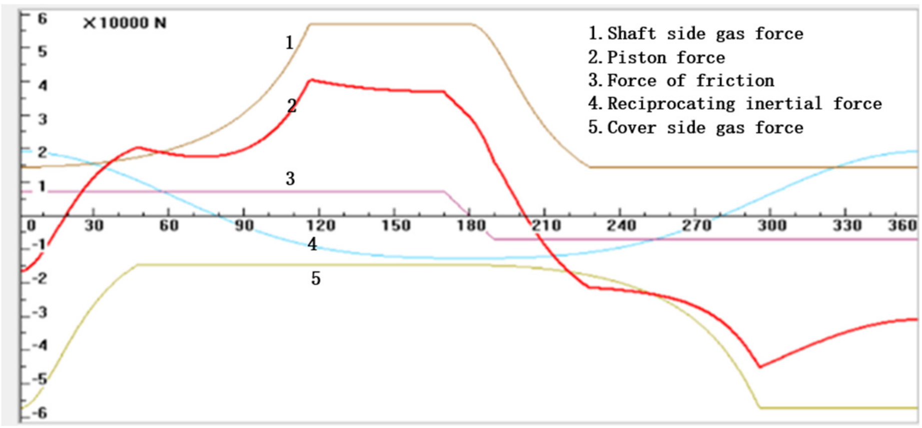

FIG. 1 Working force curve of compressor connecting rod

The crankshaft is known to reach the maximum tension at 118 degrees, the maximum tension is in the rotation to 298 degrees when the maximum pressure.

Table.1 Maximum connecting rod force and piston force

Angle	Inertia force	Gas forces (cover side)	Gas forces (shaft side)	The piston force
118	9.25×10^3N	1.48×10^4N	5.7×10^4N	4.01×10^4N
298	5.69×10^3N	5.75×10^4N	1.44×10^4N	4.52×10^4N

The integrated piston force will be F_P decomposed into a component force F_n perpendicular to the centerline of the cylinder and a component force F_l, in the direction of the connecting rod axis, and the mathematical relationship between the connecting rod force F_l and the piston force is:

$$F_l = \frac{F_P}{\cos\beta} = \frac{F_P}{\sqrt{1-\lambda^2(\sin\theta)^2}} \tag{5}$$

Where: β is the pressure angle, θ is the crankshaft angle of rotation, λ is the crank connecting rod ratio.

$$\text{Tensile state: } F_l=\frac{4.01\times10^4}{\sqrt{1-0.2^2\times(\sin 118)^2}}=4.09\times 10^4 \tag{6}$$

$$\text{state of compression: } F_l=\frac{4.52\times10^4}{\sqrt{1-0.2^2\times(\sin 298)^2}}=4.59\times 10^4 \tag{7}$$

3.3. Pressure Angle of connecting rod at work

According to engineering experience, the contact load distribution and angle of action between the small head and crosshead of the connecting rod and the large head and crankshaft have certain laws in the working of the connecting rod, and their selection has a great influence on the calculation results. In this paper, the following load distribution is adopted, the contact surface load is uniformly distributed along the connecting rod, in the plane of the connecting rod according to the law of cosine function, and the load size is uniformly distributed along the thickness of the connecting rod. The load distribution is shown in Figure.2.

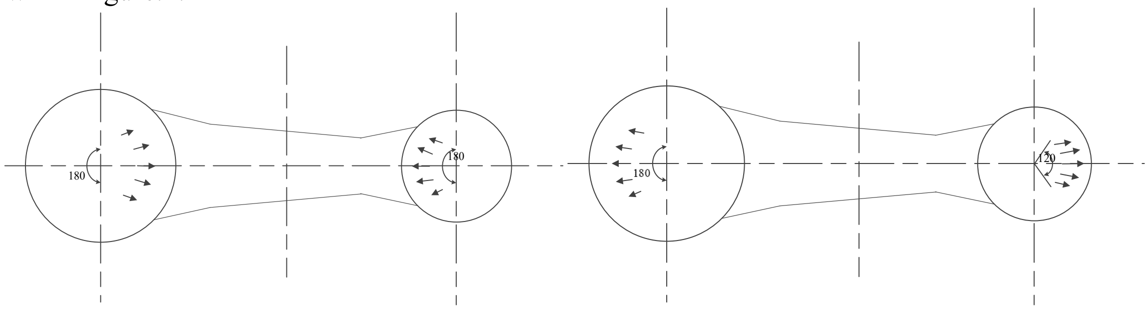

FIG. 2 Diagram of contact load distribution under tension and compression

When the connecting rod is compressed, both the small head and the large head are subjected to a load at an angle of 180 degrees, and the load size is evenly distributed. When the connecting rod is pulled, where the small head is subjected to a contact load range of 120 degrees, and the large head is subjected to a contact load of 180 degrees by the crankshaft.

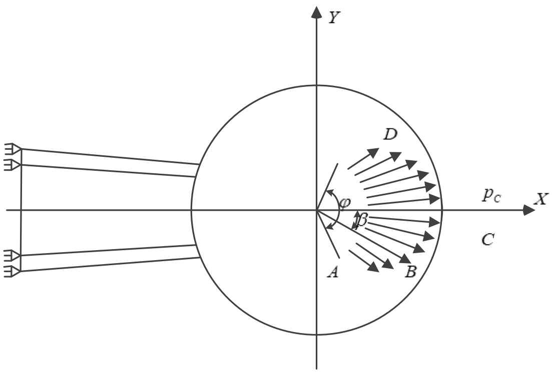

FIG. 3 The load distribution law of small head under tension

Let B be any point of arc ADC, $\angle COB=\beta$,P_B is the distributed load value at point B, P_c is the distributed load value at the point of maximum stretch or maximum compression. q is the angular scale factor: q=π/φ.

Pressure distribution formula:

$$\text{P=Acos}(\frac{\alpha}{\varphi}\pi) \tag{8}$$

Force calculation formula:

$$F=\int_{-\frac{\varphi}{2}}^{\frac{\varphi}{2}} A\cos(\frac{\alpha}{\varphi}\pi)\cos\alpha RLdL \tag{9}$$

When q = 1:

$$F=\pi ARL/2 \tag{10}$$

$$p=A\cos(\frac{\alpha}{\varphi}\pi) \tag{11}$$

When q≠ 1:

$$p=\frac{F(\pi^2-\varphi^2)\cos(\frac{\alpha}{\varphi}\pi)}{2R\varphi L\pi\cos\frac{\varphi}{2}} \tag{12}$$

Where: R is the radius of the small head, L is the width of the small head, F is the maximum tensile force or maximum pressure, and φ is the specified angle.

The force set at any point on the surface of the maximum tension of the small head is calculated as:

The tension on the small head of the connecting rod:$13.109\cos(1.5\alpha)$N/mm^2

The pressure on the small head of connecting rod:$11.244\cos\alpha$N/mm^2

4. Topology Optimization of Compressor Connecting Rod Structure

4.1. Establishment of the connecting rod CAE model

According to the physical object, establish the 3D model of the connecting rod, import the 3D model established by solidworks into hyperworks, clean up the connecting rod model, clean up some rounded corners, screw holes and some other parts that have no effect on the overall structural forces, in order to divide a higher quality mesh. The compressor connecting rod is geometrically cut and divided into design area and non-design area. For easy installation, the connecting rod is separated, the lower half of the big head is integrated with the rod body, and the upper half is bolted to the rod cover, so the rod body is used as the design area, and the small head and big head of the connecting rod are used as the non-design area. The model is divided by tetrahedral units, the average size of the units is 3mm, there are 383854 units and 811096 nodes. The model is shown in the Figure.4.

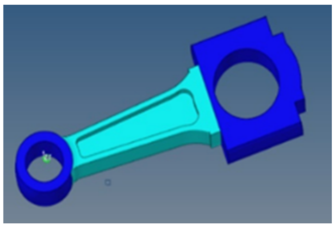

FIG.4 Conceptual diagram of connecting rod

The connecting rod is subjected to two operating conditions, namely tension and pressure. The maximum values are 4.09×10^4N and -4.59×10^4N.In addition, the connecting rod is installed with the small head in interference fit with the bushing, thus subjecting the small head to additional stresses. The large end of the connecting rod is subjected to a force range of 180 degrees during operation, with constraints established at 180 degrees on each of the left and right sides of the large end, respectively, limiting 6 degrees of freedom.

The material of connecting rod is 45 steel, density is $7.859g/cm^3$, modulus of elasticity is 2.1×10^6N/mm, Poisson's ratio is 0.3, yield limit is 350MPA.

4.2. Optimization of the connecting rod CAE model

In order to improve the service life of the connecting rod, the local stress of the connecting rod is set to be less than half of the yield limit of the connecting rod, so the stress does not exceed 175 MPA as a constraint, and the ratio of the volume of the design area before and after optimization is not greater than 0.3 as a constraint. In this case, two conditions are set up, and the multi-case strain energy is weighted by the compromise planning method, and the Optistruct custom function is used to define the compromise planning formula.

Figure.5 shows the number of iterations of the topology optimization of the compressor connecting rod and the strain energy size, it can be seen that with the increase of iteration steps, the function image converges and the strain energy of the connecting rod decreases in both working conditions. Figure.6 shows the first two orders of intrinsic frequencies of the connecting rod, and the optimized connecting rod has an increase in both orders of intrinsic frequencies.

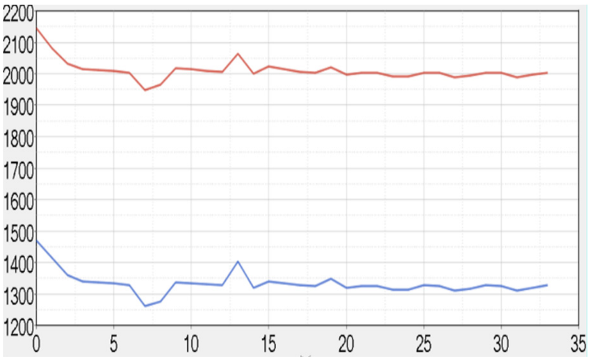

FIG.5 Iteration of strain energy

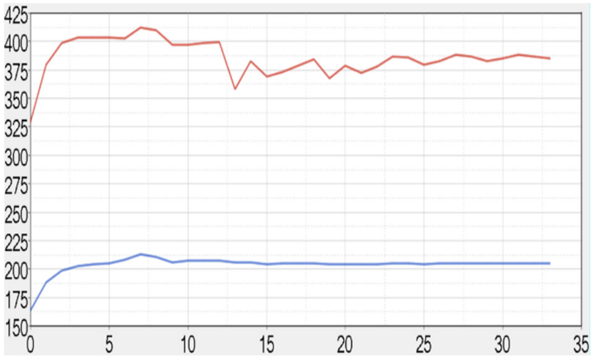

FIG.6 Iteration of frequency

5. Compressor Connecting Rod Redesign and Verification

The minimum relative threshold is set to 0.15 to see the final optimized cell density distribution map. According to the optimized material density distribution map, the density distribution map is re-imported into hypermesh and redesigned with solid work. Figure.7 shows the redesigned connecting rod.

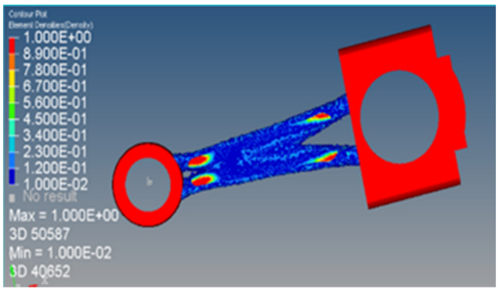

FIG.7 Topology optimization results

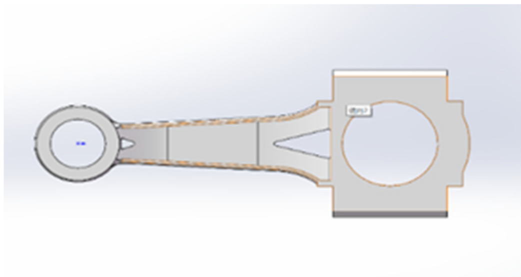
FIG. 8 Redesigned connecting rod

The static strength of the designed connecting rod is analyzed again. Hyperworks is used to mesh it, apply force and load, and solve the static strength. The stress cloud diagram is obtained.

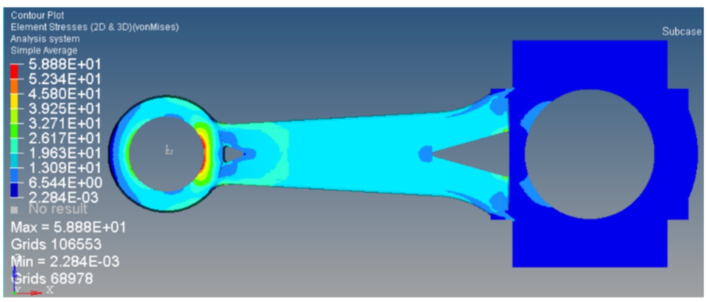

FIG.9 Stress cloud diagram under maximum pressure condition

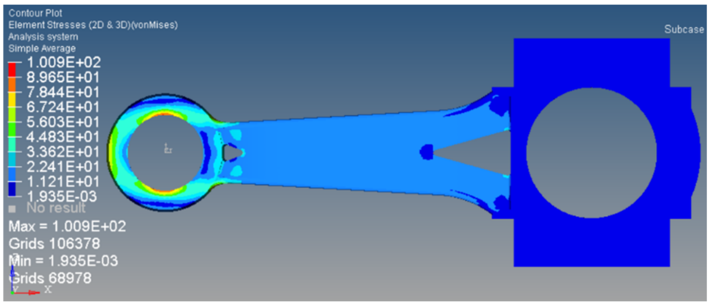

FIG.10 Stress cloud diagram under maximum tension condition

The mass of the optimized connecting rod is reduced by 21.6%, the maximum compressive stress is 58.8mpa, and the maximum tensile stress is 100.9mpa, which is less than the stress constraint 175MPA.The performance of the connecting rod is improved and good results are achieved.

6. Conclusion

Based on variable density method and compromise programming method, a multi-objective topology optimization mathematical model of compressor connecting rod is established, the material density as the design variable, the volume as the constraint, the minimum flexibility and natural frequency improvement as the goal, according to the actual working conditions of the compressor connecting rod as a constraint, and finally obtained the optimization model of the connecting rod.

(1) The optimized model is geometrically reconstructed and the feasibility of the model is revalidated.

(2) Through the topology optimization of the connecting rod, the material of minor parts is removed to satisfy the stiffness and strength conditions, and the mass of the connecting rod is successfully reduced and the performance of the part is improved. It provides a theoretical basis for the design and improvement of the connecting rod.

Ackonwledgements

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