Investigation on the vibration balance approach for four-row star type reciprocating compressors

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Investigation on the vibration balance approach for four-row star type reciprocating compressors

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Abstract. Four-row star type reciprocating compressor was regarded as a compressor with low vibrations. However, an experiment of the new developed compressor shows serious vibration because of unbalanced force caused by the unique structural arrangement. In this paper, the investigation on the vibration balance approaches of four-row star type reciprocating compressor is carried out. The effects of cylinder arrangement, thermodynamic parameters and additional force on the vibration performance are investigated, which can effectively reduce the vibration and noise of the four-row star type reciprocating compressor and provide an optimization basis for the design of this type of compressor.

Keywords: reciprocating compressor, dynamic analysis, force balance, vibration

1. Introduction

Air compressors have been used in petrochemical, metallurgy, mining and many other fields. The reciprocating air compressor has become the key of modern ship pneumatic system, which provides high-pressure air for start-stop of diesel engine, float-sink control and valve control. But the vibration caused by motor, crank connecting rod mechanism and periodic suction and exhaust process greatly reduces the reliability of compressors. The four-row star type reciprocating compressor holds the most outstanding performance with advantages such as compact structure, good force balance performance, low vibration and low noise so that it can reduce vibration due to unbalanced force effectively. [1-3]

Many scholars have studied the vibration caused by inertial force and tangential force of four-row star type reciprocating compressor. Xiaofei Jia [4] et al. quantitatively analyzed the inertial force and inertial moment of four-row star type reciprocating compressor. The dynamic balance characteristics of the compressor were obtained. Fei Shi [5] carried out thermodynamics and dynamics analysis according to the structure and working characteristics of four-row star type reciprocating compressor. Moreover, the optimization scheme of structure was proposed by studying the influence of tangential force on the compressor. Some scholars [6-8] theoretically and experimentally investigated the vibration characteristics of compressors.

However, previous research had some limitations. In practical engineering application, the vibration of four-row star type reciprocating compressor is affected by many factors. In this paper, the source of vibration is investigated based on thermodynamic and dynamic calculation, furthermore the influence of cylinder arrangement, thermodynamic parameters of first stage cylinder and additional force on the cover side of first stage cylinder on the vibration is analyzed. Finally, the reasonable solutions are obtained to provide the theoretic basis for the design and optimization of four-row star type reciprocating compressor in the future.

2. Dynamics theory

The schematic diagram of the crank-connecting rod mechanism is shown in Figure 1. Various forces including gas force, inertial force and friction force can be generated during the operation of the compressor. These forces are transmitted through the crank connecting rod mechanism to other parts. Where, the reciprocating inertial force, tangential force, lateral force and their respective moments will result in obvious vibration of the compressor.

The previous research shows the fact that when the reciprocating inertial mass of each row is the same, the resultant force of the first order reciprocating inertial force remains constant with the direction along the crank and the resultant force of the second order reciprocating inertial force is zero. Therefore, the first order reciprocating inertial force is usually balanced by increasing the balance weights. In this paper, the reciprocating inertial moment, tangential force, lateral force and overturning moment under different conditions are mainly investigated to further analyze the influence on compressor vibration.

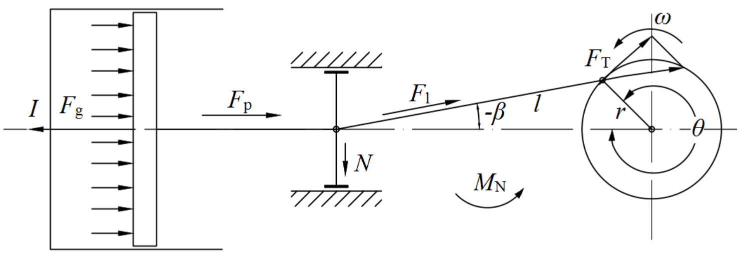


Figure 1. Crank-connecting rod mechanism

The tangential force and resistance moment of each row of the four-row star type reciprocating compressor are expressed as follows：

$$F_{\mathrm{T}}=F_{\mathrm{p}}\frac{\sin(\theta+\beta)}{\cos\beta} \tag{1}$$

$$M_{\mathrm{r}}=F_{\mathrm{T}}r \tag{2}$$

Where F_T is the tangential force, F_p is the piston force, θ is the crank angle, β is the angle between the connecting rod and the axis of the cylinder, M_r is the resistance moment, r is the length of crank.

The lateral force and overturning moment of each row of the four-row star type reciprocating compressor are expressed as follows：

$$N=F_{\mathrm{p}}\tan\beta \tag{3}$$

$$M_{\mathrm{N}}=F_{\mathrm{p}}r\frac{\sin(\theta+\beta)}{\cos\beta} \tag{4}$$

Where N is the lateral force, M_N is the overturning moment which is equal to resistance moment.

The schematic diagram of reciprocating inertial force and moment are illustrated in Figure 2. Where, I_1, I_2, I_3, I_4 are the reciprocating inertial forces of each row respectively; M_{I1}, M_{I2}, M_{I3}, M_{I4} are the reciprocating inertial moment of each row respectively. Where, the reciprocating inertial moment in the first and second rows point to the negative direction of the y-axis, and the reciprocating inertial moment in the third and fourth rows point to the positive direction of the x-axis.

Therefore, the reciprocating inertial moment along x-axis M_{Ix} and the reciprocating inertial moment along y-axis M_{Iy} are expressed as follows:

$$M_{Ix} = \frac{a}{2} I_3 + \frac{a}{2} I_4 \tag{5}$$

$$M_{Iy} = \frac{3a}{2} I_1 + \frac{3a}{2} I_2 \tag{6}$$

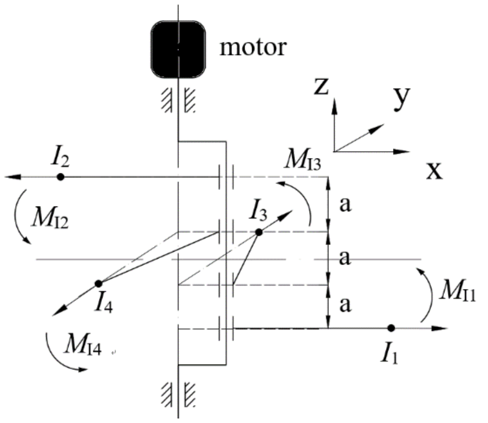


Figure 2. Schematic diagram of reciprocating inertial force and moment

The basic parameters of the four-row star type reciprocating compressor used in this paper are listed in Table1.

Table 1. Basic parameters

Stage	p_s [MPa]	p_d [MPa]	n [r/min]	η	fluid
1	0.1	0.47	1470	70%	air
2	0.47	2.07	1470	70%	air
3	2.07	9.1	1470	70%	air
4	9.1	40	1470	70%	air

3. The effect of cylinder arrangement

The cylinder arrangement directly affects the reciprocating inertial moment, tangential force, lateral force and overturning moment of four-row star type reciprocating compressor, and further affects the stability of compressor. Therefore, reasonable arrangement of cylinder is one of the key methods to solve the vibration problem of four-row star type reciprocating compressor. The arrangement of cylinders is mainly divided into the following two aspects: the arrangement of each cylinder along the crankshaft and the arrangement with different relative staggered angles of the four rows of cylinders.

3.1. Cylinder arrangement along crankshaft

The arrangements of the cylinders of different rows along crankshaft include three types, namely a, b and c, shown in Figure 3.

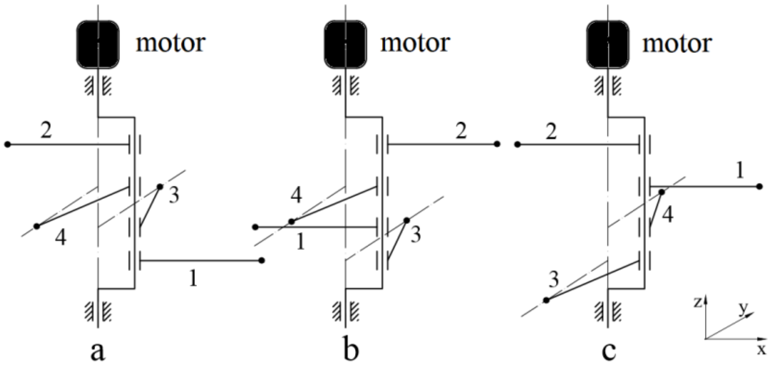
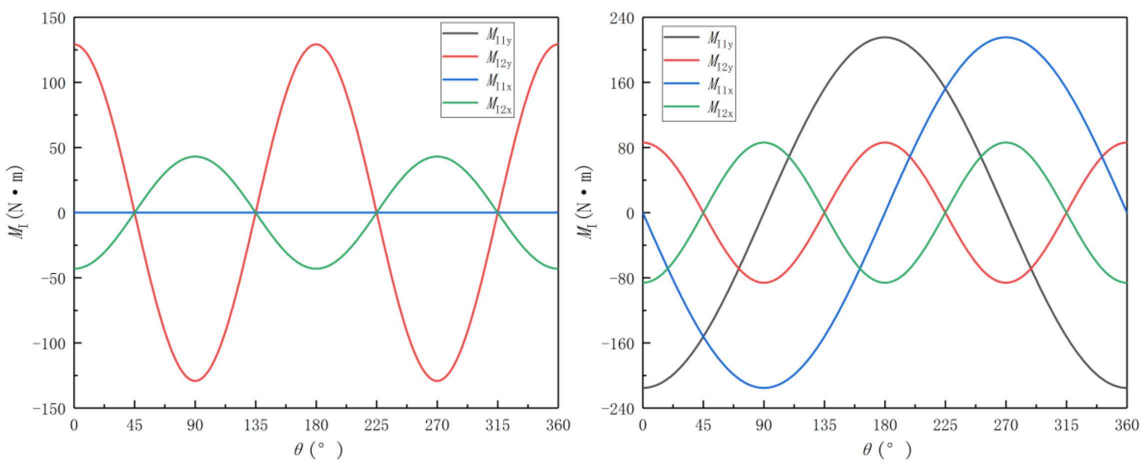


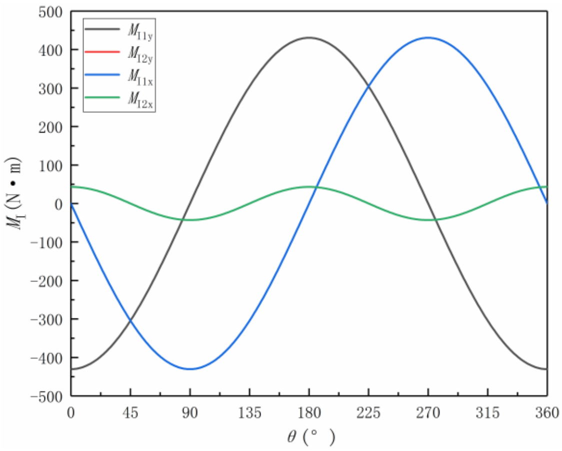
Figure 3. The cylinder arrangements along crankshaft

The variations of the reciprocating inertial moment of three cases with the crank angle are shown in Figure 4. Where, M_{I1x} is the component of the first order reciprocating inertial moment along the x-axis, M_{I1y} is the component of the first order reciprocating inertial moment along the y-axis, M_{I2x} is the component of the second order reciprocating inertial moment along the x-axis, M_{I2y} is the component of the second order reciprocating inertial moment along the y-axis。

Figure 4 indicates that the first order reciprocating inertial moment of case a is completely balanced while the second order reciprocating inertial moment changes with the crank angle. The first order and second order reciprocating inertial moments of case b are all unbalanced. For case c, although both first order and second order reciprocating inertial moment are unbalanced, the second order reciprocating inertial moment is less than 50 N·m. The existing four-row star type reciprocating compressor is generally arranged as case a, ignoring the second order reciprocating inertial moment. However, the resultant moment of the first order reciprocating inertial moment of case c remains unchanged during a period, and the direction is always perpendicular to the direction of the crank. Table 2. shows the reciprocating inertial moment of case c. Therefore, a pair of symmetrical balance weights can be added in the opposite direction to form a moment equal to the first order reciprocating inertial moment with an opposite direction. Furthermore, the centrifugal forces cancel each other and have no influence on the performance of the compressor. Generally, case c is a great balanced structure.



(a) (b)



(c)

Figure 4. The diagram of reciprocating inertial moment in different cases:

(a) case a; (b) case b; (c) case c

Table 2. The reciprocating inertial moment of case c

Crank Angle [°]	M_{I1y}[N • m]	M_{I1x}[N • m]	M_{I1}[N • m]	Angle between M_{I1} and x-axis [rad]
0	-430.513	0.000	430.513	4.712
90	0.000	-430.513	430.513	3.142
180	430.513	0.000	430.513	1.571
270	0.000	430.513	430.513	0.000

3.2. Cylinder arrangement with different relative staggered angles

The relative staggered angle of each row also has a significant impact on the vibration of the compressor. In this section, six types of cylinder arrangements with different relative staggered angles are adopted to analyze the impact of the relative staggered angle, as shown in Figure 5. For example, as shown in figure 5a, take the direction of first row as positive direction of x-axis, θ_1 being taken as a baseline, the phase angles of other rows are as follows: $\theta_2 = \theta_1 + \frac{\pi}{2}$, $\theta_3 = \theta_1 + \pi$, $\theta_4 = \theta_1 + \frac{3\pi}{2}$ 。

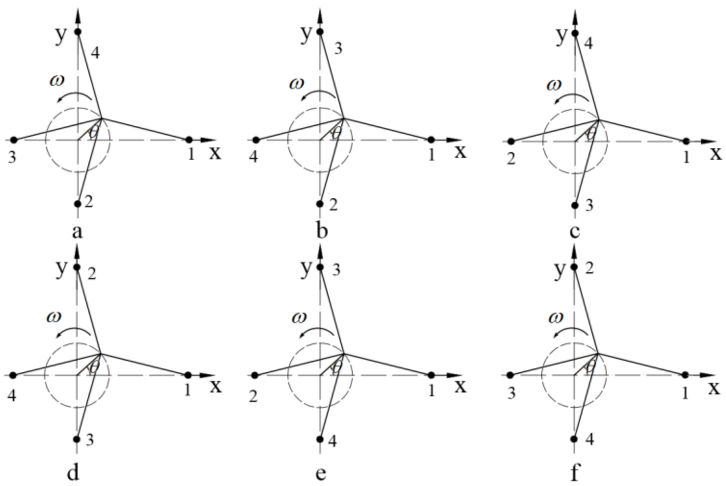


Figure 5. Arrangements in different relative angles

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The variations of the tangential forces of each row with the crank angle are shown in Figure 6, reflecting the change of the resistance moment. The total tangential force, average value and standard deviation of the six cases are illustrated in Figure 7 and Figure 8 respectively. The force of each row is not affected by the cylinder arrangement. However, there are phase differences between four rows in different cases, and different matching results in different total tangential forces corresponding to different rotation angles.

The results show that the average tangential forces of the six cases are the same. In addition, the standard deviation of the tangential force in case c is the smallest, indicating that the total tangential force has the smallest fluctuation and the best stability. It is because that the tangential forces of all rows in case c can be better offset and the amplitude of the total tangential force is the smallest. Therefore, the vibration caused by tangential force can be improved by adopting case c.

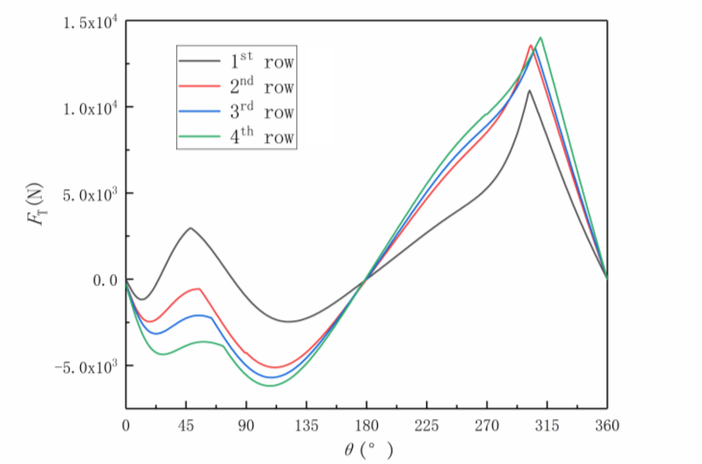

Figure 6. Tangential forces in four rows

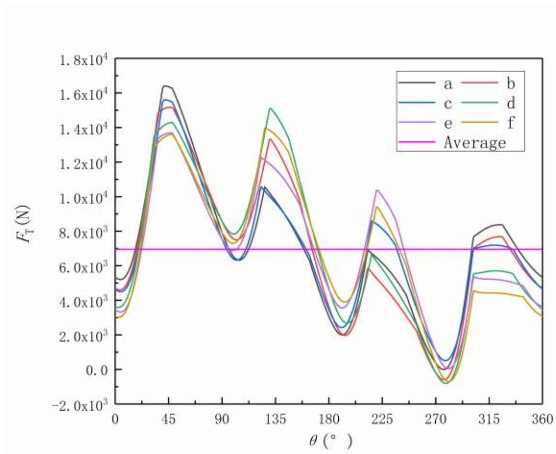

Figure 7. Total tangential forces in six cases

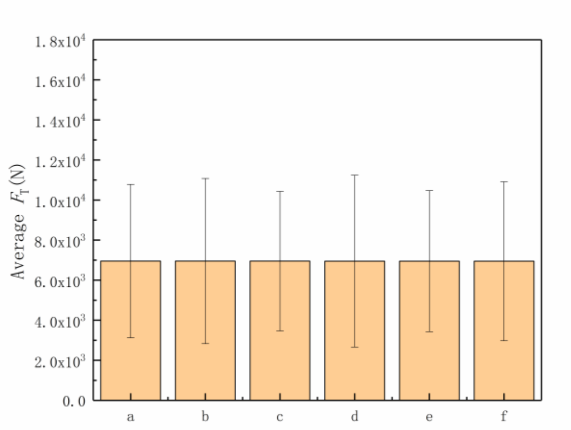

Figure 8. Averages and standard deviations

The similar conclusion can be drawn as for the lateral force and overturning moment. The variations of lateral forces and overturning moments of the four rows are shown in Figure 9 and Figure 10. The same trend can be observed, indicating that the lateral force and overturning moment of each row are not affected by the arrangement. However, due to the different phase angle of each row under different arrangements, there are differences in the combined action of forces in all rows, which can be reflected by the resultant overturning moment.

The overturning moment, average value and standard deviation of each case are shown in Figure 11 and Figure 12 respectively. It can be seen that the standard deviation of resultant overturning moment of case c is the smallest, indicating that its changes are more uniform and the compressor is more stable. This is also due to the fact that the overturning moments in all rows under this arrangement can be better offset and the minimum amplitude of the overturning moments is obtained. Therefore, the vibration of compressor can be effectively reduced by adopting case c.

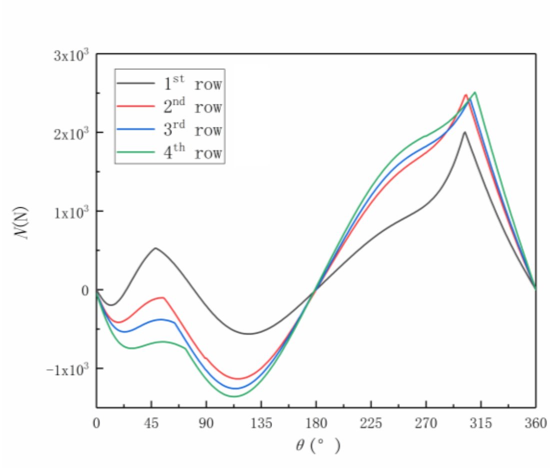

Figure 9. Lateral forces in four rows

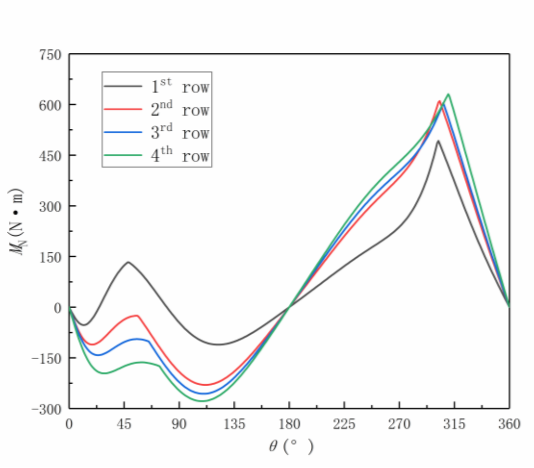

Figure 10. Overturning moments in four rows

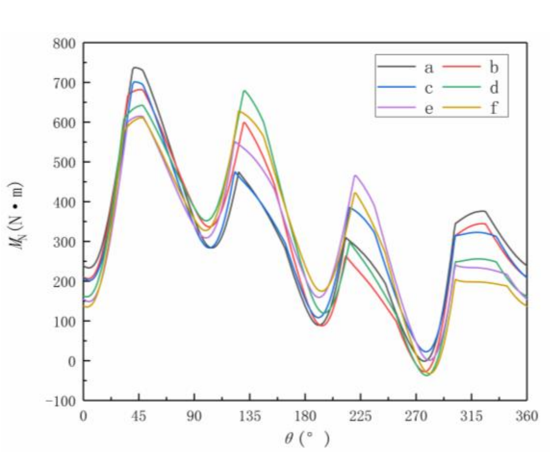

Figure 11. Resultant overturning moments in six cases

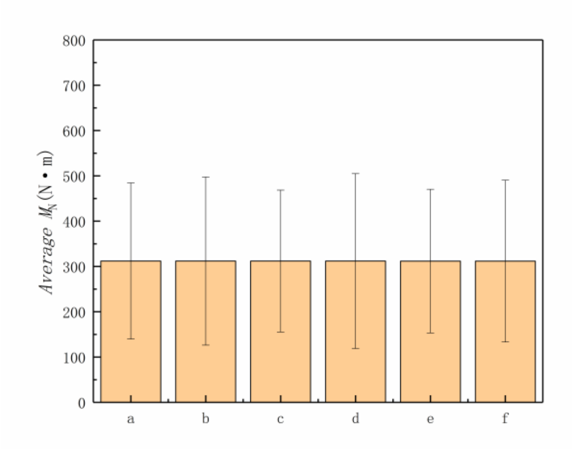

Figure 12. Averages and standard deviations

4. The effects of thermodynamics parameters

According to the above results, it can be found that there are four peaks for the overturning moment of four-row star reciprocating compressor. In addition, the four peaks decrease in turn. The difference between the first peak and the fourth peak is very large. The overturning moment with large fluctuation is one of the main reasons for vibration. In order to decrease the first peak value and increase the fourth peak value, the first peak value of the first row should be decreased and the fourth peak value should be increased. Therefore, the pressure ratio of the first stage, cylinder diameter and relative clearance volume should be considered to decrease the vibration.

In this paper, three cases are carried out for calculation, as listed in Table 3. Where p_{d1} is the exhaust pressure of the first stage cylinder, α is the relative clearance volume of first stage cylinder, D is the first stage cylinder diameter.

Table 3. The three cases

case	p_{d1}[MPa]	α	D[mm]
1	0.47	0.085	220
2	0.47	0.13	230
3	0.49	0.13	230

The variations of overturning moment with crank angle of three cases are shown in Figure 13. It can be observed that the pressure ratio, relative clearance volume and cylinder diameter of the first stage cylinder play a significant role in reducing the enormous fluctuation of resultant overturning moment.

According to Figure 14, the average values in the three case are basically the same (about 310 N·m). However, with the increase of the pressure ratio, relative clearance volume and cylinder diameter of the first stage cylinder, the standard deviation of the resultant overturning moment decreases. The fluctuation of the moment slows down obviously, which is mainly reflected in the decrease of the difference between the first and fourth peaks of the resultant overturning moment. It can be seen that the stability of four-row star type reciprocating compressor can be significantly improved by increasing relative clearance, pressure ratio and cylinder diameter of the first stage cylinder.

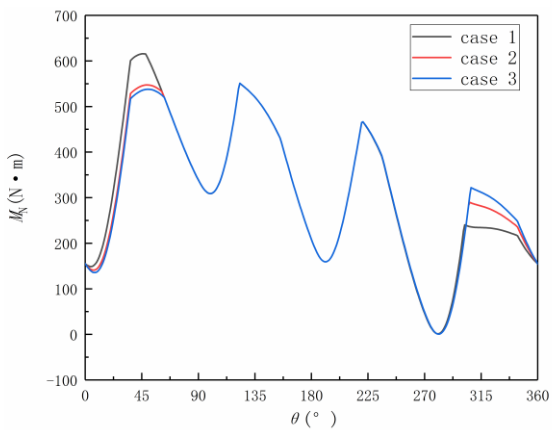

Figure 13. The resultant overturning moment

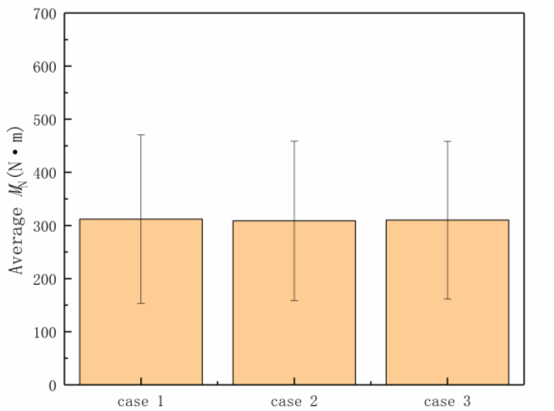

Figure 14. Averages and standard deviations

5. The effect of additional force

From the above analysis, it can be seen that reducing the first peak value and increasing the fourth peak value of the first stage cylinder can effectively reduce the vibration of the compressor caused by the overturning moment. The same effect can also be achieved by applying additional force to the cover side of the first stage cylinder as figure 15 shows; Where F_a is the additional force; and the value and direction of the additional force are constant in the working process. Therefore, constant additional forces of 3500 N, 4000 N and 5760 N are applied to the cover side of the first stage cylinder in this section with arrangement in case c respectively. The effect of additional force on resultant overturning moment is analyzed by comparing with the condition without additional force.

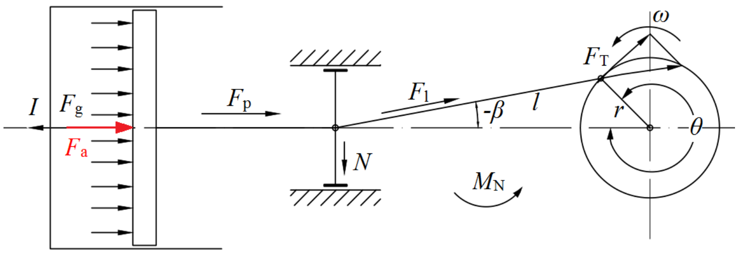

Figure 15. Scheme of additional force

Figure 16 illustrates that different additional forces have different effects on resultant overturning moment. The distributions of the first peak value and fourth peak value can be improved and the fluctuation of the resultant overturning moment can be reduced by increasing the force on the cover side of the first stage cylinder. In addition, the other two peak values are also affected. Obviously, adding additional force can reduce the resultant overturning moment of the first half of period and increase that of the second half of period. With the increase of additional force, the difference between the overturning moment of the first half of period and that of the second half of period decreases firstly and then increases. Figure 17 also confirms the phenomenon and shows that the case of adding 3500N force has the smallest standard deviation. Therefore, adding additional force can increase the stability of the four-row star type compressor without changing the structure of the existing compressor.

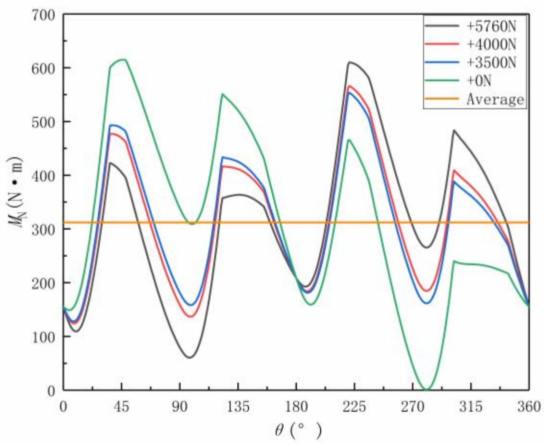

Figure 16. The resultant overturning moments

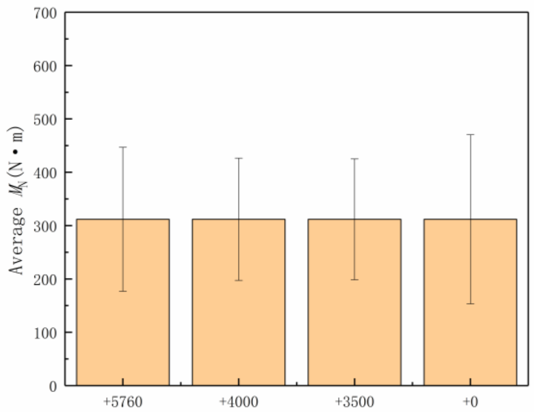

Figure 17. Averages and standard deviations

6. Conclusions

In this paper, the effects of cylinder arrangement, thermodynamic parameters and additional force on the vibration performance of a four-row star type reciprocating compressor are investigated. Some performance parameters such as reciprocating inertial moment, tangential force, lateral force and overturning moment are compared specifically. The following conclusion can be drawn:

- The cylinders arranged along the crankshaft in case c are easily to be balanced. The resultant moment of the first order reciprocating inertial moment of case c remains unchanged in a period and the direction is always perpendicular to the direction of the crank. Therefore, a pair of symmetrical balancing weights can be added in the reverse direction to balance the inverted reciprocating inertial moment.
- The relative staggered angle of each row also has a significant impact on the vibration of the compressor. The tangential forces at all rows in case c can be better offset and the amplitude of the total tangential force is minimal, the total tangential force has the smallest fluctuation and the best stability in case c. Therefore, the vibration caused by tangential force can be apparently improved by case c.

- The fluctuation of the moment slows down and the stability of four-row star type reciprocating compressor is significantly improved by increasing relative clearance, pressure ratio and cylinder diameter of the first stage cylinder.
- Adding additional force can increase the stability of the four-row star type compressor. This approach reduces the resultant overturning moment of the first half of period and increase the overturning moment of the second half of period. With the increase of force, the difference between the overturning moments of the first half of period and that of the second half of period decreases firstly and then increases.

References

[1] Mei L，Siying S. Principles of Piston Compressor [M]. China Machine Press, 1987.
[2] Yongzhang Y. Reciprocating Compressor [M]. China Machine Press, 1982.
[3] Yan X, Wei Z, Ping H, et al. The Vibration Characteristic Analysis of Marine Air Compressor [J]. Machinery Design & Manufacture, 2015(11):197-200.
[4] Xiaofei J , Yuchi P , Xiaoling Y , et al. Dynamic Characteristics Analysis of Four-row Star Type and Double-V Type Reciprocating Compressors — Part 1: Dynamic Analysis for Four-row Star Type Reciprocating Compressors [J]. Compressor Technology, 2017.
[5] Fei S. Optimization Analysis of the Crank-link Mechanism Layout Scheme in Marine Star-type Compressor [J]. Fluid Machinery, 2014.
[6] Bin S, Jian W, Bin W. Research and treatment of basic resonance of a certain type of Marine air compressor [J]. Vibration, testing and diagnosis, 2006, 26(2):142-145.
[7] Jiang Z, Zongchang Q, Rong C, et al. Analysis and Calculation of External Force and Its Balance for Four Stages Nitrogen Hydrogen Reciprocating Compressors [J]. Compressor Technology, 2014
[8] Chaobo L, Jingjun L, Zhenhai Z, et al. Experimental study on vibration characteristics of star compressor [J]. Journal of Wuhan University of Technology (transportation science and engineering), 2018(3).