Dynamic analysis of reciprocating compressor with two revolute joint clearances

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Abstract. Dynamic analysis of reciprocating compressor with two joint clearances is studied. In order to investigate the nonlinearity of the system, the dynamic equation of the system is established based on Lagrange method. By changing the parameters of the system, the response of the system under different sizes of joint clearance and crankshaft speed is obtained. From the simulation results of the system, we can see the influence of crankshaft speed and joint clearance on the system dynamics. By calculating the phase diagrams and the maximum Lyapunov exponents, it can be concluded that the motion of the system is chaotic.

Keywords: reciprocating compressor, joint clearance, phase diagram, Lyapunov exponent, chaos.

1. Introduction
Reciprocating compressor is important fluid machinery in petrochemical industry. It carries the task of transporting gas raw materials and providing power for process system. Compared with centrifugal compressor, reciprocating compressor has many advantages, such as wide pressure range, high thermal efficiency, low manufacturing cost, etc. It is especially suitable for process environment requiring high pressure and low flow rate. In order to meet the needs of modern petrochemical industry, the development trend of reciprocating compressor is advancing towards the direction of high pressure, high efficiency, low energy consumption and low noise. However, the large-scale equipment makes the structure more complex, daily maintenance management and inspection and maintenance more difficult. Dynamic analysis of reciprocating compressor with joint clearances can provide an effective basis for system fault diagnosis.

Many scholars have done a lot of work in the research of mechanism dynamics with joint clearance. Flores et al. [1, 2] investigated clearance and lubrication effects on the crank-slider mechanism and they also analyzed the spatial mechanism with joint clearance [3]. I. Khemili, L. Romdhane studied the mechanism dynamics with clearance and flexible rod using ADAMS and ABAQUS software [4]. The dynamic of a two-stage reciprocating compressor with four joint clearances was investigated using...
Lagrange method and ADAMS software [5]. Xiao, Shungen et al. studied the dynamics of reciprocating compressor with clearance and subsidence fault by using Lagrange equation method. While discussed the effects of crankshaft speed, joint clearance size and subsidence size on system dynamics respectively, and discussed the nonlinearity of the system through phase trajectory, FFT, Poincare section and maximum Lyapunov exponent.

In order to study the dynamic characteristics of reciprocating compressor with clearance by means of Lagrange equation, the dynamic equation of the system is established in section 2. The influence of clearance and crankshaft speed on the system is discussed in section 3. In section 4, the nonlinearity of the system is studied by phase diagram and maximum Lyapunov exponent.

2. The dynamic equation of reciprocating compressor with two revolute joint clearances

Simplify the reciprocating compressor with clearance, as shown in Fig.1. There is a clearance between the joint connection position of crankshaft and connecting rod and the position of connecting rod and crosshead pin, where the clearance is expressed by a massless rod and the size of the clearance is expressed by a massless rod length. Two clearances in Fig.2 are represented by \( r_1 \) and \( r_2 \) respectively. Figure 2 is a simplified closed-loop vector diagram of the system. \( \theta, \theta_2 \) is the angle between crankshaft and connecting rod and X axis in horizontal direction, \( \theta_1, \theta_3 \) is the angle between two massless rods \( r_1, r_2 \) and X axis in horizontal direction. In this paper, assuming \( r_1 = r_2 \), the crankshaft speed is constant.

The degree of freedom of the analysis system is three, and the dynamic equation of the system is Eq. 1.

\[
\frac{d}{dt} \left( \frac{\partial E}{\partial q_i} \right) - \frac{\partial E}{\partial q_i} + \frac{\partial U}{\partial q_i} = Q_i
\]  

where \( E \) is the kinetic energy of the system and \( U \) is the potential energy of the system, \( Q_i \) is the nonconservative generalized force corresponding to the generalized coordinate \( q_i \). According to the vector relation of Figure 2, the system equation is deduced and calculated by using MATLAB software.

![Figure 1. Schematic representation of reciprocating compressor with two-clearance revolute joints](image1)

![Figure 2. Vector representation of reciprocating compressor two-clearance revolute joints](image2)

3. The influence of system parameters

The existence of joint clearance makes the motion of reciprocating compressor more complex. Here the influence of clearance and speed on the motion of reciprocating compressor is explained by changing the crankshaft speed and clearance size.
3.1. Effect of Crankshaft Speed on System

Fig. 3. is Crosshead X direction acceleration at different driving speeds. It can be seen from Fig. 3 that with the increase of crankshaft speed, the influence of clearance on system motion increases. However, the movement trend of cross head acceleration is similar under three rotational speeds.

![Figure 3. Crosshead X direction acceleration at different driving speeds](image)

3.2. Effect of Joint Clearance Size on System

Fig. 4. is Crosshead X direction acceleration at different clearance size. Fig. 4 shows that the influence of clearance on system motion increases with the increase of hinge clearance. Under the condition of constant crankshaft speed, the influence of clearance value on the acceleration of crosshead is very obvious.

![Figure 4. Crosshead X direction acceleration at different clearance size](image)

4. Investigation of System Nonlinear

![Figure 5. phase diagram of the velocity and acceleration of the crosshead at different clearance size](image)

When studying dynamic problems with clearances, it is often found that the system becomes unstable, and even the motion of the system is chaotic [7]. Whether the dynamic behavior of the system is chaotic or not, qualitative and quantitative judgments are often carried out at the same time. Phase diagram method is a common method for qualitative judgment. One of the common methods of quantitative judgment is to calculate the maximum Lyapunov exponent of the system. If the maximum Lyapunov exponent of the system is positive, the motion of the system is chaotic. Both methods are used in this
article. Fig.5. is phase diagram of the velocity and acceleration of the crosshead at different clearance size and Fig.6. is phase diagram of the velocity and acceleration of the crosshead at different driving speeds. From these two Figures, we can see that the system may be chaotic.

![Figure 6](image-url)

**Figure 6.** phase diagram of the velocity and acceleration of the crosshead at different driving speeds

When the speed of crankshaft is 300 r/min, the maximum Lyapunov exponents of the system with clearance values of 0.05 mm, 0.1 mm and 0.2 mm are 0.0012, 0.0075 and 0.0074, respectively.

![Figure 7](image-url)

**Figure 7.** Lyapunov exponent at different clearance size

The maximum Lyapunov exponent of the system is 0.0066, 0.0081 and 0.0074 when the clearance of two clearances is 0.15mm, the crankshaft speed is 240 r/min, 360 r/min and 480 r/min, respectively.

![Figure 8](image-url)

**Figure 8.** Lyapunov exponent at different driving speeds

5. **Conclusion**

The dynamic behavior of reciprocating compressor with clearance is analyzed in the paper. The dynamic equation of the system is established by Lagrange method. Assuming that the crankshaft speed is constant and the two clearances are equal, the change of the speed and the acceleration of the system in different clearances are given. Furthermore, in order to study the dynamic nonlinearity of the system, the qualitative judgment of the velocity and acceleration phase diagrams and the quantitative judgment of the maximum Lyapunov exponent are used respectively. The results show that chaos appears in the motion of the system with two revolute joint clearances.

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