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DYNAMICAL ANALYSIS OF SCROLL COMPRESSOR WITH THE COMPLIANT CRANK MECHANISM

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ABSTRACT

The machining precision in the scroll compressor with the compliant crank mechanism is not required so high as that with the fixed throw crank, but the sealing performance is better than the later’s, therefore the scroll compressor with the compliant crank mechanism operates at higher efficiency. In this study, the characters of the compliant crank mechanism are discussed, while the Oldham coupling and ball coupling mechanisms are separately used to restrict the orbiting scroll rotation. The movement behaviors of the orbiting scroll and the compliant crank mechanism are analysed in detail when the ball coupling mechanism is adopted, their dynamical models are developed on the basis of the force analysis. This research is useful for the optimization design of the compliant crank mechanism.

INTRODUCTION

When the scroll compressor operates in the ideal condition, the orbiting scroll moves around the center of the fixed scroll at a small crank radius, while its rotation is close confined, the wrap axes of two scrolls are parallel to each other, the wraps are in mesh to form the crescent shaped pockets. But in the actual situation, it is quite difficult to insure the perfect mesh, owing to the effects of the machining and installing precisions, so the leakages through the mating clearances occur, these affect the compressor performance. In order to solve this problem, some mechanisms are required, one of them is the compliant crank mechanism. The compliant crank mechanism has been analyzed in a number of papers [1−3] in recent years, while the Oldham coupling is adopted to restrict the rotation of the orbiting scroll. The dynamical analysis of scroll compressor with the compliant crank mechanism is carried out in this paper, while the ball coupling mechanism is used to restrict the orbiting scroll rotation.
ANTI-ROTATION COUPLING COMPARISON

There are three kinds of the anti-rotation coupling used in scroll compressor for the present, one is the Oldham coupling, the second is the ball coupling, the last one is the multi-crank mechanism. When the compliant crank mechanism is adopted in scroll compressor, only the Oldham coupling and the ball coupling are available for use, but they have the different effects on the orbiting scroll. The comparison of their effects is made as follows:

Oldham coupling:
Advantage: The rotation is close confined.
Disadvantage: (1) It is difficult to machine.
(2) The reciprocating inertia force can’t be balanced.
(3) There exist the losses of sliding friction.

Ball coupling:
Advantage: (1) The coupling supports the orbiting scroll in the axial direction additionally.
(2) It is easy to machine
(3) The losses of rolling friction are less.
Disadvantage: The orbiting scroll may rotate slightly.

So the advantages of the ball coupling are obvious, therefore, the following research on the compliant crank mechanism is carried out on the basis of adopting ball coupling.

MOVING BEHAVIOR

The typical structure of the compliant crank mechanism is shown in Fig. 1. When the eccentric bushing swings around the crank post, the change of the orbiting radius (r) will take place accordingly. The relationship between the frame, crankshaft, eccentric bushing and the orbiting scroll is simplified as the four-arm hinge mechanism as shown in Fig. 2. In order to avoid the over-location of the orbiting scroll and minimize the leakage in the central part, the change of the wrap thickness is adopted. When two scrolls are in mesh, the roll angle range of the contact point is from $\Phi_1$ to $(\Phi_1 + 2\pi)$, where $\Phi_1$ is the starting roll angle of the inner curve. The orbiting radius defined by the ball coupling is a little greater than that defined by the wraps in the ideal condition, so as to insure the wrap contact.

(1) In the ideal condition, the degrees of freedom are 2 according to the analysis of the four-arm hinge mechanism, so the flank of the orbiting scroll wrap contacts with the fixed scroll's in two positions as shown in Fig. 3, the twisted angle ($\alpha$) of the orbiting scroll is zero, the swing angle ($\beta$) of the eccentric bushing is zero as well.

(2) When the orbiting scroll deviates from the ideal position ($\alpha \neq 0$), as shown in Fig. 4, and the swing angle is not the maximum ($\beta \neq \beta_{max}$), the degrees of freedom are 2, so the flank
of the fixed scroll wrap contacts with the orbiting scroll’s in a position and restricts one degree of freedom, the ball coupling restricts the other degree of freedom.

(3) When the swing angle is equal to the maximum ($\beta = \beta_{\text{max}}$), the degree of freedom is 1. If the flanks of two scroll wraps contact, the angular rotation of the orbiting scroll around the center of eccentric bushing is $\xi_1$; if the ball coupling restricts the degree of freedom, the angular rotation is $\xi_2$. If $\xi_1 < \xi_2$, the flanks of the wraps contact, if $\xi_1 > \xi_2$, the ball coupling restricts the rotation of the orbiting scroll.

The orbiting radius decreases as long as the orbiting scroll deviates from the ideal position. Under the normal operating condition, the wrap of the orbiting scroll is twisted towards the center by the tangential gas force, so the outer curve of the orbiting scroll contacts with the inner curve of the fixed scroll.

**DYNAMICAL ANALYSIS**

(1) Under the ideal condition, $\alpha = 0$, $\beta = 0$, the forces acting on the orbiting scroll are shown in Fig. 5.

- Gas forces: tangential $F_\theta$, radial $F_r$, axial $F_t$
- Centrifugal force $F_c$
- Frictional force of the axial gas force: $\mu_t F_t$
- Flank contacting (sealing) forces and frictional forces: $F_{s1}, \mu_s F_{s1}, F_{s2}, \mu_s F_{s2}$
- Reaction forces between orbiting scroll and eccentric bushing: $F_{do}, \mu_d F_{do}, F_{dr}, \mu_d F_{dr}$

The forces acting on the eccentric bushing are shown in Fig. 6.

- Centrifugal force $F_{co}$
- Reaction forces between the eccentric bushing and the crank post: $F_{p\theta}, F_{pr}$
- Reaction forces between eccentric bushing and orbiting scroll: $F_{do}, \mu_d F_{do}, F_{dr}, \mu_d F_{dr}$

The force balance equations of the orbiting scroll are obtained as follows:

$$F_{s1} + F_{s2} - F_{dr} + \mu_d F_{do} - F_c + F_t = 0$$

$$F_{do} + \mu_d F_{dr} - \mu_s F_{s1} - \mu_s F_{s2} - F_\theta - \mu_t F_t = 0$$

The moment balance equations of the orbiting scroll are obtained as follows:

When $0 \leq \theta \leq (2.5\pi - \Phi_1)$ ($\theta$ is the crank angle)

$$\mu_d R_o \sqrt{F_{do}^2 + F_{dr}^2} - F_{s1} \cdot a + F_{s2} \cdot a - \mu_s F_{s1} \cdot a (1.5\pi + \alpha_o - \theta)$$

$$+ \mu_s F_{s2} \cdot a (2.5\pi - \alpha_o - \theta) + F_r \cdot \Delta l \cdot \sin \theta + F_g (r/2 + \Delta l \cdot \cos \theta) + \mu_t F_t \cdot \sin \theta \cdot y_t$$

$$- \mu_t F_t \cdot \cos \theta \cdot x_t + F_c \cdot \sin \theta \cdot x_c + F_c \cdot \cos \theta \cdot |y_c| = 0$$

When $(2.5\pi - \Phi_1) \leq \theta < 2\pi$,

$$\mu_d R_o \sqrt{F_{do}^2 + F_{dr}^2} - F_{s1} \cdot a + F_{s2} \cdot a - \mu_s F_{s1} \cdot a (3.5\pi + \alpha_o - \theta)$$

$$+ \mu_s F_{s2} \cdot a (4.5\pi - \alpha_o - \theta) + F_r \cdot \Delta l \cdot \sin \theta + F_g (r/2 + \Delta l \cdot \cos \theta) +$$
\[ \mu F_c \sin \theta \cdot y_1 - \mu F_c \cos \theta \cdot x_1 + F_c \sin \theta \cdot x_G - F_c \cos \theta \cdot |y_G| = 0 \]

Where \( a \) is the base circle radius of scroll involute, \( R_o \) is the radius of bearing. \( \alpha_o \) is the half involute thickness angle, \( \Delta l \) is the eccentricity of the scroll wrap, \((x_G, y_G)\) is the gravity center of the orbiting scroll, \((x_r, y_r)\) is the coordinate point of the reacting force of the axial gas force.

The force and moment balance equations of the eccentric bushing are obtained as follows:

\[ F_{co} + F_{dr} - F_{p_r} \cos \gamma - F_{p_r} \sin \gamma = 0 \]

\[ F_{dr} + \mu_4 F_{dr} - F_{p_r} \cos \gamma - F_{p_r} \sin \gamma = 0 \]

\[ F_{p_r} \cdot R_2 \cdot \cos \gamma - F_{p_r} \cdot R_2 \cdot \sin \gamma - \mu_4 R_o \sqrt{F_{dr}^2 + F_{dr}^2} = 0 \]

Where \( \xi \) and \( \xi' \) are shown in Fig. 6.

(2) When the twisted angle of the orbiting scroll is \( \alpha \), and the swing angle of the eccentric bushing is not the maximum \( (\beta \neq \beta_{\text{max}}) \), the orbiting radius of the compliant crank is \( r' \), the wrap flanks contact only in one position, so \( F_{z_2} = 0 \). Because the ball coupling restricts the rotation of the orbiting scroll under this condition, the reaction forces between the orbiting scroll and the ball coupling exist, \( F_b, \mu_3 F_b \). The forces acting on the orbiting scroll are shown in Fig. 7, where \( C \) is the flank contact point, \( O_1 \) is the center of rotation, \( O_2 \) is the center of the fixed scroll wrap, \( O_3 \) is the driving center of the orbiting scroll, \( O_4 \) is the center of the orbiting scroll wrap, the force and moment balance equations of the orbiting scroll are obtained as follows:

\[ F_{c_1} \sin (\theta + \Delta \theta_1 - \Delta \theta_2 - \alpha) - F_c \cos (\theta + \Delta \theta_1 - \Delta \theta_2 - \alpha) + \mu_4 F_{c_1} \sin (\theta_{a_1} - \alpha) \]

\[ - F_{c_1} \cos (\theta_{a_1} - \alpha) + F_c \cos (\theta + \Delta \theta_1 - \alpha) + \mu_4 F_{c_1} \sin (\theta + \Delta \theta_1 - \alpha) + \mu_b F_{c_1} \sin (\theta + a_b - \alpha) - F_{c_1} \cos (\theta + \alpha_b - \alpha) + F_{d_1} \cos (\theta + \Delta \theta_1 - \alpha) \]

\[ - \mu_4 F_{d_1} \sin (\theta + \Delta \theta_1 - \alpha) - F_{d_1} \cos (\theta + \Delta \theta_1 - \alpha) - \mu_4 F_{d_1} \cos (\theta + \Delta \theta_1 - \alpha) = 0 \]

\[ F_c \cos (\theta + \Delta \theta_1 - \Delta \theta_2 - \alpha) + F_c \sin (\theta + \Delta \theta_1 - \Delta \theta_2 - \alpha) + F_{c_1} \sin (\theta_{a_1} - \alpha) + \mu_b F_{c_1} \cos (\theta + a_b - \alpha) + \mu_4 F_{d_1} \sin (\theta + \Delta \theta_1 - \alpha) \]

\[ - F_{d_1} \cos (\theta + \Delta \theta_1 - \alpha) - F_{d_1} \sin (\theta + \Delta \theta_1 - \alpha) - \mu_4 F_{d_1} \cos (\theta + \Delta \theta_1 - \alpha) = 0 \]

\[ \mu_4 R_o \sqrt{F_{d_1}^2 + F_{d_1}^2} - (F_{c_1} \sin \theta_{a_1} + \mu_4 F_{c_1} \cos \theta_{a_1}) \cdot (F_{d_1} \sin \theta_{b} + \mu_4 F_{d_1} \cos \theta_{b}) \]

\[ + \mu_b F_r \left( l_r \cos \theta_{b} + r_{bb} \right) + F_r \cdot \Delta l \cdot \sin (\theta + \Delta \theta_1 - \Delta \theta_2 - \alpha) + F_{c_r} (r''/2 + \Delta l \cdot \cos (\theta + \Delta \theta_2 - \alpha)) + F_c (y_{r_2}) + \mu_4 F_c \cos (\theta + \Delta \theta_1 - \alpha) x_1 \]

\[ + F_c (\sin (\theta + \Delta \theta_1 - \alpha) x_G + F_c \cos (\theta + \Delta \theta_1 - \alpha) \cdot |y_G| = 0 \]

Where \((x_1', y_1')\) is the coordinate point of the reacting force of the axial gas force, \( r_{bb} \) is the radius of the circular recess of the ball coupling. The forces acting on the eccentric bushing are shown in Fig. 8, the force and moment balance equations of the eccentric bushing are
obtained as follows:

\[ F_{d\theta}\sin(\theta+\Delta\theta) + \mu_d F_{d\theta}\sin(\theta+\Delta\theta) - F_r\cos(\theta+\Delta\theta) + \mu_d F_{d\theta}\cos(\theta+\Delta\theta) \]

\[ + \mu_d F_{w}\cos(\theta+\Delta\theta) - F_{wo}\cos\theta_{co} - F_{w}\sin(\theta+\xi) + F_{w}\cos(\theta+\xi) = 0 \]

\[ F_{d\theta}\cos(\theta+\Delta\theta) + \mu_d F_{d\theta}\cos(\theta+\Delta\theta) + F_r\sin(\theta+\Delta\theta) \]

\[ - \mu_d F_{w}\sin(\theta+\Delta\theta) + F_{wo}\sin\theta_{co} - F_{w}\cos(\theta+\xi) - F_{w}\sin(\theta+\xi) = 0 \]

\[ F_{w}\cos(\xi' - \beta) - F_{w}\cos(\theta+R3)(1 - (R_{co}e)) \]

\[ + (r+R3)^2 - r'^2)/(2R_{co}(r+R3))^2) = 0 \]

\[ F_{w}\cos(\xi' - \beta) - F_{w}\cos(\theta+R3)(1 - (R_{co}e)) \]

\[ + (r+R3)^2 - r'^2)/(2R_{co}(r+R3))^2) = 0 \]

\[ F_{w}\cos(\xi' - \beta) - F_{w}\cos(\theta+R3)(1 - (R_{co}e)) \]

\[ + (r+R3)^2 - r'^2)/(2R_{co}(r+R3))^2) = 0 \]

Where \( R_{co} \) is the radius of the gravity center of the eccentric bushing.

(3) When the swing angle is equal to the maximum, \( \beta = \beta_{max} \):

(1) the wrap flanks contact, the forces acting on the orbiting scroll are similar to the state (2), while the force \( F_b \) is equal to zero. The forces acting on the eccentric bushing is also similar to the state (2), while the extra reaction force \( F_{sl} \) between the eccentric bushing and its stopper exists in this situation. The force and moment balance equations of the eccentric bushing are obtained as follows:

\[ F_{d\theta}\sin(\theta+\Delta\theta) + \mu_d F_{d\theta}\sin(\theta+\Delta\theta) - F_r\cos(\theta+\Delta\theta) + \mu_d F_{d\theta}\cos(\theta+\Delta\theta) \]

\[ - F_{wo}\cos\theta_{co} - F_{w}\sin(\theta+\xi) + F_{w}\cos(\theta+\xi) + F_{sl}\sin(\theta+\xi-\beta) = 0 \]

\[ F_{d\theta}\cos(\theta+\Delta\theta) + \mu_d F_{d\theta}\cos(\theta+\Delta\theta) + F_r\sin(\theta+\Delta\theta) \]

\[ - \mu_d F_{w}\sin(\theta+\Delta\theta) + F_{wo}\sin\theta_{co} - F_{w}\cos(\theta+\xi) - F_{w}\sin(\theta+\xi) + F_{sl}\cos(\theta+\xi-\beta) = 0 \]

\[ F_{w}\cos(\xi' - \beta) - F_{w}\cos(\theta+R3)(1 - (R_{co}e)) \]

\[ + (r+R3)^2 - r'^2)/(2R_{co}(r+R3))^2) = 0 \]

\[ F_{w}\cos(\xi' - \beta) - F_{w}\cos(\theta+R3)(1 - (R_{co}e)) \]

\[ + (r+R3)^2 - r'^2)/(2R_{co}(r+R3))^2) = 0 \]

\[ F_{w}\cos(\xi' - \beta) - F_{w}\cos(\theta+R3)(1 - (R_{co}e)) \]

\[ + (r+R3)^2 - r'^2)/(2R_{co}(r+R3))^2) = 0 \]

(2) the ball coupling restricts the orbiting scroll rotation, the forces acting on the orbiting scroll are similar to the state (2), while the force \( F_{sl} \) is equal to zero, the forces acting on the eccentric bushing are the same as the state(1).

**CONCLUSION**

The characters of the compliant crank mechanism are discussed, while the Oldham coupling and the ball coupling mechanism are separately used to restrict the orbiting scroll rotation. The movement behaviors of the orbiting scroll and the compliant crank mechanism are analysed in detail when the ball coupling mechanism is adopted, their dynamical models are developed on the basis of the force analysis.
REFERENCE


Fig. 1 Compliant crank mechanism

Fig. 2 four-arm hinge mechanism

Fig. 3 Ideal position

Fig. 4 Twisted position
Fig. 5 Forces acting on orbiting scroll (ideal condition)

Fig. 6 Forces acting on eccentric bushing (ideal condition)

Fig. 7 Forces acting on orbiting scroll (twisted condition)

Fig. 8 Forces acting on eccentric bushing (twisted condition)