THE IMPACT OF BILGE PUMPS BEARING BUSH AND CRANKSHAFT JOURNAL CLEARANCE ON VIBRATION CHARACTERISTICS

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The influence of the clearance between different connecting rod bearing bush and crankshaft journals on the force of the moving pair are analyzed and kinematic characteristics and vibration characteristics of the pump transmission under different clearance boundary conditions are studied by using a two - state gap contact - collision model. The vibration characteristics of the bilge pump transmission under different clearance conditions are obtained by ADAMS software calculating and analyzing.

Keywords: bilge pumps clearance vibration

1. Introduction

The wear of motion mechanism of bilge pump is the main factor affecting its performance. In this part, the two-cylinder double-acting bilge pump is taken as the research object, the wear fault mechanism is analyzed and studied. The modelling method of contact-separation two state model is adopted, and the wear fault between motion pairs is expressed simply by clearance. Thus, the mechanical model of wear failure of connecting rod-crankshaft journal system is established.[1]

In the process of modelling, considering the actual working state of bilge pump, the interrelation among components and the phenomenon of fluid pulsation, the relationship between wear gap change and dynamic response is analyzed by numerical solution and ADAMS simulation. It provides theoretical basis for fault detection and diagnosis of bilge pump.

2. Analysis of Wear Mathematical Model of Motion Mechanism

The crank - slider body composition diagram is shown in figure 1. The rigid body system consisted of crankshaft (B1), connecting rod (B2), slide block (B3), piston pole (B4) and piston (B5). Mass, the centre of mass, and the force are labelled \( m \), \( C \) and \( F \) separately. In this part, the dynamic equation of motion pair wear of reciprocating bilge pump is established by means of contact-separation two-state
model, and the wear clearance of crankshaft and journal mechanism of connecting rod is taken as an example. [2]

![Figure 1: stress analysis of connecting rod crankshaft neck system](image)

Taking the connecting rod as the object of study, the force on the connecting rod is analyzed separately. The force with clearance is shown in figure 2, and the dynamic equation is obtained as follows.

\[
\begin{align*}
F_{12}^n + F_{12}' + F_{32}^y &= \mu F_{12}\cos \theta + \tau_A, \\
F_{12}' &= \mu F_{12}\sin \theta - \tau_A, \\
F_{32}^y &= \tau_B, \\
F_{32}^x &= \tau_B. 
\end{align*}
\]

In the formula 1 and formula 2, \(\ddot{x}_{c2}\) and \(\ddot{y}_{c2}\) represents the acceleration of the mass center of the connecting rod in the x and y directions, \(F_{12}^n\) and \(F_{12}'\) represents the normal and tangential reaction force of the crankshaft acting on the connecting rod, and \(F_{32}^x\) and \(F_{32}^y\) represents the horizontal and vertical reaction force of the piston acting on the connecting rod.

Take the moment of momentum for point B, and the conservation law of the moment of momentum is as follows

\[
J_B\dot{\beta} = F_{12}'[L_2\cos(\beta - \theta) + R_A] - F_{12}^nL_2\sin(\beta - \theta) + m_2gL_{c2}\cos \beta + m_2\ddot{x}_B L_{c2}\sin \beta. 
\]

In the formula, \(J_B\) represents the moment of inertia of the rod to point B, and \(R_A\) represents the radius of the inner ring of the bearing with the shaft sleeve radius.

According to the geometric relationship between components,

\[
x_{c2} = x_B - L_{c2}\cos \beta. \\
y_{c2} = L_{c2}\sin \beta. 
\]

The differential of the upper form is obtainable.
In this paper, a two-state contact model is used to model the geometry of the components.

\[ \dot{x}_c = \dot{x}_B - \dot{\beta}^2 L_c \cos \beta + \dot{\beta} L_c \sin \beta \quad (6) \]

\[ \dot{y}_c = -\dot{\beta}^2 L_c \sin \beta - \dot{\beta} L_c \cos \beta \quad (7) \]

In this paper, a two-state contact model is used to model the geometry of the components.

\[ d_x = L_1 \cos \alpha - L_2 \cos \beta - x_B \quad (8) \]

\[ d_y = L_1 \sin \alpha - L_2 \sin \beta \quad (9) \]

In the formula, \( d_x \), \( d_y \) represents the relative displacement of the shaft pin and the sleeve in the x and y directions. Thus, the normal phase and tangential velocity of the shaft sleeve relative to the shaft pin at the contact point can be obtained.

\[ v_{12}^n = d_x \cos \theta - d_x \sin \theta (\dot{\alpha} - \dot{\beta}) r_A \quad (10) \]

\[ v_{12}^t = d_y \sin \theta + d_x \cos \theta \quad (11) \]

In the formula, \( r_A \) represents the shaft pin radius. The above equation is solved by using the contact separation two state equation. The normal contact deformation is \( \sigma \), the wear clearance is \( d \), and the displacement of the shaft sleeve relative to the shaft pin is \( \delta \). And then \( \sigma = d - \delta \).

\[ u(\sigma) = \begin{cases} 1 & \sigma \geq 0 \\ 0 & \sigma < 0 \end{cases} \quad (12) \]

Contact collision model equation with two states:

\[ F_{12}^n = (K_n + C_n v_{12}^n) u(\sigma) \quad (13) \]

\[ F_{12}^t = -f \text{sign}(v_{12}^t) F_{12}^n + C_t v_{12}^t u(\sigma) \quad (14) \]

In the formula, \( K \) represents shaft sleeve stiffness coefficient, \( C_n \) represents normal damping coefficient, \( C_t \) represents tangential damping coefficient and \( f \) represents Coulomb friction coefficient. Then the force of the clearance collision force in the X and Y directions is respectively:

\[ F_{AX} = u(\sigma)(-F_{12}^t \sin \theta + F_{12}^n \cos \theta) \quad (15) \]

\[ F_{AY} = u(\sigma)(F_{12}^t \cos \theta + F_{12}^n \sin \theta) \quad (16) \]

### 3. Analysis of liquid excitation force of bilge pump

During the operation of the bilge pump, the connecting rod journal mechanism runs periodically and the piston moves back and forth, so the flow rate acting on the piston changes periodically, which will produce pulsating pressure on the piston surface. Will also have a huge impact on the whole machine vibration.

#### 3.1 Instantaneous flow calculation

In the calculation of bilge pump flow, the influence of clearance on bilge pump can be neglected because of its relatively large flow rate. The crank-link system motion is shown in figure 2.

The displacement of the reciprocating piston is

\[ x_B = L_1 + L_2 - (L_1 \cos \alpha + L_2 \cos \beta) \quad (15) \]

In the formula, \( L_1 \) represents the length of the crank and \( L_2 \) represents the length of the connecting rod. The geometric relationships of the components are as follows:

\[ \cos \beta = \sqrt{1 - \lambda^2 \sin^2 \alpha} \quad (16) \]

In the formula, \( \lambda = L_1/L_2 \), it is called the crank-link ratio.
\[ x_B = L_1(1 - \cos \alpha) + L_2(1 - \sqrt{1 - \lambda^2 \sin^2 \alpha}), \quad \alpha = \omega t \]  \hspace{1cm} (17)

In the formula, \( \omega \) represents crank speed. Because the value of \( \lambda \) (0~0.25) is small, it is negligible.

\[ 1 - \lambda^2 \sin^2 \alpha \approx 1 \]

So the flow rate of the pump is

\[ Q_1 = A \dot{x}_B = AL_1 \omega (\sin \alpha + \frac{\lambda \sin 2\alpha}{2}) = AL_1 \omega \sin \alpha \]  \hspace{1cm} (18)

According to the above formula, the theoretical transient flow of bilge pump fluctuates with sinusoidal function. The double-cylinder double acting bilge pump is the superposition of the transient flow of the single-cylinder single-acting pump with a phase difference of 180 degrees.

### 3.2 Instantaneous pressure calculation

The two cylinders of the double-acting pump are always in the stage of suction and discharge, and the phase difference between the two cylinders is 180 degrees, so the combined pressure in the cylinder is the vector sum of the suction discharge pressure mentioned following.

#### 3.2.1 Suction pressure calculation

As shown in figure 3, if the surface of the piston head of cylinder 1 and 2 is directly in contact with one end of the liquid, the instantaneous energy of the fluid flowing through the cross section 1-1 is:

\[ E_{1-1} = \rho Q_1 Z_1 + P_1 Q_1 / g + \rho Q_1 \mu_1^2 / 2g \]  \hspace{1cm} (19)

In the formula, \( Q_1 \) represents flow through section 1-1, \( \rho \) represents liquid density and \( \mu_1 \) represents fluid velocity.

If the surface section of the liquid is 2-2, the instantaneous energy of the fluid flowing through the cross-section 2-2 is:

\[ E_{2-2} = \rho Q_1 Z_0 + P_2 Q_1 / g \]  \hspace{1cm} (20)

According to the energy balance equation of bilge pump:

\[ E_{1-1} + E_{BA} + E_{A1} = E_{2-2} \]  \hspace{1cm} (21)

In the formula, \( E_{BA} \) represents instantaneous Energy lost by flow through BA Section of No.1 pump cylinder, \( E_{A1} \) represents instantaneous Energy lost by flow through A1 Section of No.1 pump cylinder.

\[ P_1 = P_a + \rho Z_0 g - \rho g (Z_1 + h_{z1} + h_{g1} + K_{z1} + K_{g1}) - P_1 - \rho \mu_1^2 / 2 \]  \hspace{1cm} (22)

In the formula, the subscript \( z \) represents the liquid resistance loss, the subscript \( g \) represents the liquid inertial pressure head, and \( Z \) indicates the liquid level height. After calculation, the suction pressure of bilge pump liquid can be obtained.
### 3.2.2 Discharge pressure calculation

The discharge process of bilge pump liquid is the reverse process of the suction process. The liquid in the cylinder is compressed by piston to increase the total energy and liquid pressure of the liquid, so that the liquid can overcome the resistance in the process of discharging liquid and drain the liquid from the cylinder. And can meet the bilge pump discharge pressure requirements.

According to the above derivation of the whole process of suction pressure of bilge pump, the equation of energy balance in the process of liquid discharge can be obtained recursively.

\[
P_2 = P_c + \rho Z_c g + \rho \mu^2/2 - \rho \mu_2^2/2 + \rho g (h_{z2} + h_{g2} + K_{z2} + K_{g2})
\]

(23)

### 4. Numerical calculation

On the basis of the above theoretical calculation and deduction, the combined simulation of MATLAB and ADAMS is carried out. The pressure of piston and the drive of turbine worm are added to the model during the movement of crank and connecting rod mechanism of bilge pump. The different wear gap conditions of crank and connecting rod system are compared and analyzed respectively. According to the actual working conditions of bilge pump, the flexible treatment of crank is carried out, and the contact and force relationships of each component are fully considered, and the kinematics and vibration characteristics of crankshaft before and after flexibility are compared.

The ode15s Solver in MATLAB and GSTIFF solver using SS2 equation in ADAMS were used to run the simulations. Relative tolerance 1e-3 and absolute tolerance 1e-6 were set.

#### 4.1 Velocity curve of mass center of rigid crankshaft connecting rod

When the crankshaft is rigid, the clearance between the crankshaft and the crank is 0 mm, 0.5 mm, 1.5 mm respectively, and the kinematics is simulated by ADAMS. The simulation results are shown in figure 4 with zuoliangan.CM_Velocity.X represents velocity of left connecting rod and youliangan.CM_Velocity.X represents velocity of right connecting rod.
Contrast figure 4, it can be found that when there is no gap in the motion pair, the connecting rod movement is more stable, the speed has no big change, basically changes according to the sine curve; When the gap increases gradually, the velocity curve fluctuates more and more, and the peak value begins to appear near the sinusoidal curve. When the gap increases to 1.5mm, the velocity curve has a very large peak value, and there is a particularly large velocity change near the sinusoidal curve, and the motion is extremely unstable.

4.2 Velocity curve of mass center of flexible crankshaft connecting rod

For the flexible treatment of crankshaft, under the condition of flexibility, the clearance between crankshaft and connecting rod is set to be 0 mm, 0.5 mm, 1.5 mm respectively. The dynamics and kinematics of the crankshaft are simulated by ADAMS. The simulation results are shown in figure 5 as follows:
By comparing the simulation results of figure 4 and figure 5 above, it can be found that under the conditions of rigidity and flexibility, the crankshaft has a more stable motion than the rigid one when the crankshaft is in a flexible condition and has no clearance at the moving pair. There is no large fluctuation in the velocity curve. When the gap increases gradually, the velocity curve of the mass center of the connecting rod also appears the larger fluctuation and the peak value under the flexible condition, but its fluctuation is smaller than the rigid axis, the velocity curve is more stable, and basically fluctuates slightly near the sinusoidal curve. This is more in line with the actual operation of the organization.

5. Vibration law analysis

5.1 Modal response

As shown in Figure 6, when the crankshaft journal exists clearance, the mode distribution point is more dispersed, and the frequency range of the mode is wider. Because the frequency of the bilge pump has been in the state of great variation in the working process, the bilge pump is more likely to cause resonance and aggravate the vibration of the bilge pump under the condition of different working range and wear gap.
5.2 Frequency response

As shown in figure 7 above, the frequency corresponding to the frequency response function of vibration acceleration is different in different gap states. The larger the gap, the larger the resonance frequency, and the closer the frequency band of bilge pump is, that is, the easier resonance occurs. Therefore, in bilge pump, resonance frequency should be avoided as far as possible, and the wear of bilge pump can be judged by comparing and simulating its vibration frequency.

6. Conclusion

A calculation method for two-cylinder double-acting bilge pump was brought forward in this paper. First, wear mathematical model was built to simulate the clearance of crank linkage accurately. Then, instantaneous flow and pressure were calculated using MATLAB, as a load on bilge pump. At last, the impact of bilge pumps bearing bush and crankshaft journal clearance on vibration characteristics was conducted using ADAMS.

REFERENCES
