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Research on Dynamic Characteristics of Rub-Impact of Progressive Cavity Pump with Rotation Speed

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Abstract. The dynamic characteristics of Progressive Cavity Pump (PCP) have an important influence on the stability of oil wells string system. A nonlinear dynamics model of rotor system was presented. The equations of unbalance rotor were established by the Lagrange approach and the vibration characteristics of the rotor system under rub-impact was analyzed by used the modern nonlinear dynamics and bifurcation theories, through numerical calculation. The bifurcation diagrams, time domain charts and Poincaré maps were obtained to analyze dynamic characteristics of the system and the results reveal the multiform complex nonlinear dynamic behavior of the rotor-bearing system under rub-impact. Moreover, the influence of the speed on the relatively stable speed of the rotor system was analyzed. These analysis results provide theoretical bases for the rotor system's status recognition, diagnosis as well as safe and economic operation.

Keywords: component; Single Progressive Cavity Pump; Arc region; Rotor rubbing system; Numerical simulation

1. Introduction (Heading 1)

Progressive Cavity Pump has been used in oil field because of its wide application in working environment, long span of minable temperature, simple structure and small space. During the 20 years since the screw pump came into being, the PCP has made a number of high technical achievements in the research and the development of new technology and materials, and various new PCP of oil recovery emerge in endlessly [1-3]. But the problem about vibration, balance and stability of PCP for oil recovery under high speed operation is one of the significant factors restricting the development of submersible PCP. At present, the domestic and foreign scholars for screw pump rod torque, the process pipe string structure, stator rubber performance, static and dynamic characteristics of rotor rubbing and a lot of research was conducted on the influence factors such as vibration noise, at the same time, on the basis of nonlinear dynamics and bifurcation theory the dynamic response characteristics of screw pump has carried on the thorough research, and obtained many results [4-7]. Liu Xian dong and Li Qihan established the dynamic differential equation based on the rotor dynamics theory and the stator stiffness for the misalignment and mass eccentric rotor system. The dynamic response characteristics of the system are analyzed in detail after numerical simulation. Besides, they studied the harmonic characteristics of each order to deeply understand the system's rubbing response characteristics, starting from the theory of two-dimensional holographic spectrum and only considering the mass eccentricity of the rotor [8]. Xie Mentao established the dynamic simulation model of the ground rotor tester with the help of the finite element analysis software, which can be used to analyze the unbalanced response characteristics of the rotor system, and then to analyze the distribution law of unbalanced loads on each section of the rotor in each speed range [9]. Zheng Mei-ru et al. analyzed the dynamic behavior of the rotor that hit the friction rod based on the Method of Wilson-θ, and compared the motion behavior of the rotor with the corresponding integral rotor. The research results showed that the rotor had better stability. On the basis of the above researches, the dynamic characteristics of single PCP in the stator arc region are studied in this paper.

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2. Analysis of the motion characteristics of PCP

Universal coupling at the power end of rotor and the shaft at the other end stuck the rotor of single PCP in the axial direction when the rotor moves in the stator, so that the position of rotor has no change in axial displacement. The motion of rotor in the stator is a kind of planar motion, so that the motion in any section of stator-rotor movement process can be used to describe the complete motion of the single PCP. There is a reserved clearance between the metallic rotor and the rubber stator for the convenience of assembly before the oil production of single PCP. Due to the material of the rubber stator in high temperature environment will change the properties, the stator swells and makes the interference fit between stator and rotor after the oil production of single PCP. The dynamic model of the rotor system is established for studying the motion of rotor in arc region before the stator swelling.

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When rotor moves along the semicircle inner surface of stator, the rotor with 1/4 lead is equivalent to a section for mechanical analysis and establish the dynamic model. As shown in Fig. 1, the semicircular stator is completed as a whole circle for analysis. O3 is the center of stator and O2 is the rotary center of rotor. A plane rectangular coordinate system is established by taking O1 as the origin. At the initial moment,O3 and O1 coincide. During the movement process, the coordinate of the rotating center of rotor is (x,y).

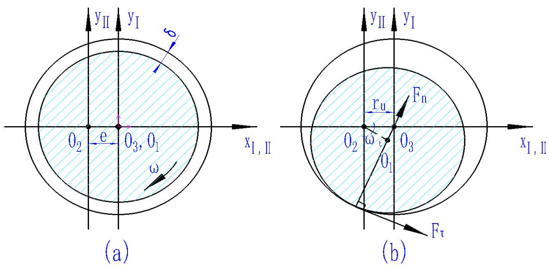

Figure 1. Force on stator and rotor when rubbing occurs

When stator and rotor are in contact, the rubber deforms under the pressure in the direction perpendicular to the contact point. The compression deformation Δl is approximated by the distance $r_{uq} = \sqrt{(x-e)^2 + y^2}$ between rotary center of O_1 rotor and geometric center of stator O_3 at the contact time and the reserved clearance δ between stator and rotor, given as: $\Delta l = \sqrt{(x-e)^2 + y^2} - \delta$. The rubbing force of the rotor at any time t can be divided into the following two cases. When $r_{uq} \le e + \delta$, the stator and the rotor are not in contact with each other and rub-impact does not occur. When $e + \delta < r_{uq}$, the stator and the rotor are in contact and the rubbing force is generated. The deformation of stator rubber is $r_{uq} - \delta$ at this time. The rubbing force is decomposed into x-y coordinate axis, given as follows:

$$\begin{cases} F_{xq} = F_n \sin \omega t + F_t \cos \omega t \\ F_{yq} = F_n \cos \omega t - F_t \sin \omega t \end{cases} \tag{1}$$

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3. Establishment of models and equations of motion

According to the modeling approach for rotor dynamics equation and the force at work of rotor in the stator, the dynamic model of stator-rotor system is established to study the stage of curvilinear motion.

$$\begin{cases} m\ddot{x} + c\dot{x} + kx + \Theta F_{xq} = \left(me\omega^2 - ke\right)\cos\omega t + ce\omega\sin\omega t \\ m\ddot{y} + c\dot{y} + ky + \Theta F_{yq} = \left(ke - me\omega^2\right)\sin\omega t + ce\omega\cos\omega t \end{cases} \tag{2}$$

Where $F_{xq} = p\Delta_x$ is the force in x-direction of rotor in stage of curvilinear motion, $F_{yq} = p\Delta_y$ is the force in y-direction of rotor in stage of curvilinear motion, $\Delta_y = \cos\omega t - \mu\sin\omega t$ is the force coefficient of rotor in y-direction, $\Delta_x = \sin\omega t + \mu\cos\omega t$ is the force coefficient of rotor in x-direction, $p = k_r$ is the model of rubbing force, $\Theta = \begin{cases} 0, r_{uq} \le e + \delta \\ 1, r_{uq} > e + \delta \end{cases}$ is selection function, .

In order to obtain the relationship between deformation and force of stressed nitrile rubber of the stator and establish the equation of rubbing force. According to the experimental results of the stator fatigue life and simulation test study under normal temperature, the model of the rubbing force of nitrile rubber was fitted by mathematical software as follows:

$$p = \alpha \cdot r_u^2 + k_r \cdot r_u + b \tag{3}$$

Where p is the rubbing force between stator rubber and rotor; r_u is the deformation of stator rubber under compression, k_r is the static rigidity of stator rubber, $\alpha \cdot r_u^2 + b$ is the nonlinear stiffness of stator rubber.

4. The simulation analysis

The speed ω of rotation is used as the control variable and the simulation is performed from 10.5rad/s to 104rad/s. The range of speed is the working speed range of PCP in most oil fields. The values of other system parameters are shown in Table 1.

Table 1. The main system parameter values

parameter	m	δ	b	μ
unit	Kg	m	N	
values	0.1176	1.8×10^{-4}	14.9153	0.2

parameter	e	k_r	α
unit	m	N/m	N/m2
values	5×10^{-3}	1.12275×10^{4}	3.49542×10^{8}

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The bifurcation diagram of the system which takes the rotating speed ω of rotor as the control variable in arc motion stage is shown in Fig. 2. In the whole process, the rotor and stator are always in contact and doing rub-impact motion, which is learned from the simulation results of bifurcation diagram. The rotating radius and the movement of the rotary center of rotor change constantly with the increase of rotating speed ω. The degree of collision between rotor and stator increases and then decreases after reaching the peak, which is periodic in the particular interval.

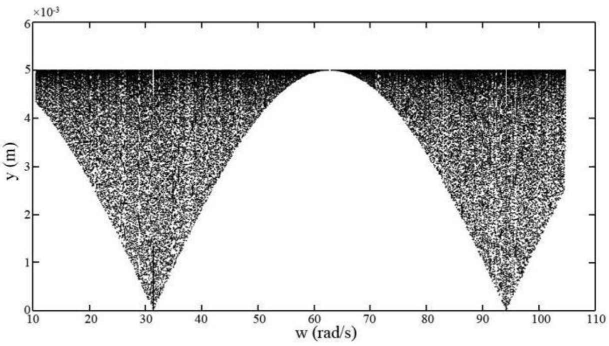

Figure 2. Bifurcation diagram of the system in the curvilinear motion stage

When the speed ω=32.2rad/s, the rotating radius reaches the minimum, the degree of collision between rotor and stator reaches the maximum and the number of movement cycles of rotary center reaches the maximum. Compared with the rubbing motion in stator, the rotary movement of rotor is minimized. The whole motion of the rotary center of rotor in the stator is changed into a strong rubbing movement circumscribed with an infinitesimal circle, which is reflected as a series of points in the Poincaré cross section. The movement of rotary center is chaotic and the collision frequency is high, as shown in Fig. 3(a); At this point, the trajectory of the geometric center of rotor is a circle with thickness on the macro level and compared with the trajectory of the rotary center of rotor shows that the movement tendency of geometric center of rotor is about the same as the motion trend of rotary center of rotor. But the whole moving area will go beyond the reserved clearance between stator and rotor. Affected by the rubbing motion of rotor in the stator, the stator rubber will be squeezed outwards by rotor, and the part that the maximum range of outer diameter of the rotor's geometric center on trajectory chart exceed the clearance value is the squeezed amount of stator rubber.

When the rotational speed ω=62.4rad/s, the rotor still keeps the rubbing contact with the stator but the collision frequency decreases. The rotating radius of rotor's rotary center increases and the motion is relatively stable. The fluctuation of the rotational center of rotor is greatly reduced but the contact form of the rub-impact between rotor and stator's inner surface remains unchanged. It indicates that the rubbing still exists in the process of movement. The phase diagram and the Poincaré cross section show that the rotary center of rotor still has multiple exercise periods. And the Poincaré cross section shows a series of dense and relatively concentrated point sets, as shown in Fig. 3(b). In this case, the exercise periods of rotor are similar to each other. The trajectory of rotor's rotary center is an approximate circle and the radius of circle is reduced significantly. Although the rotor is always in contact with the stator under rub-impact, the entire motion is more like that the rotor rolls around the inner wall of stator. It can be seen from the diameter of the circle of rotor's geometric center that the vibration amplitude of rotor is reduced compared with the previous, the extrusion degree of rubber extrusion of the rotor against stator is reduced, and the extrusion process becomes more uniform with stable rotation.

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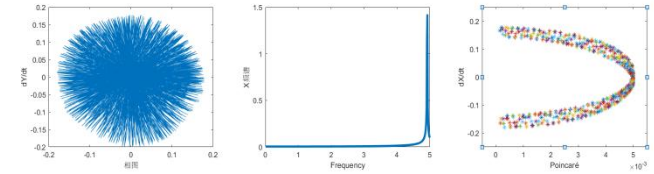
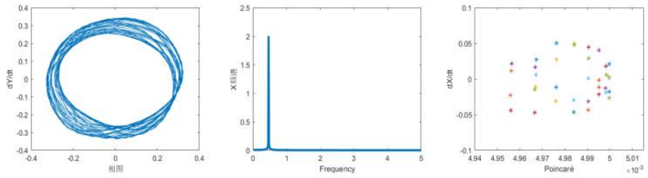


Phase diagram spectrum diagram Poincaré cross section

(a) ω =32.2rad/s



Phase diagram spectrum diagram Poincaré cross section

(b) ω =62.4rad/s

Figure 3. Phase diagram, spectrum diagram and Poincaré cross section of the rubbing response of rotor system at different speeds in the curved motion stage

The rotor enters a relatively stable stage when the rotating speed ω =62.4rad/s and enters the next unstable motion stage with the increase of the rotational speed. The instability is at its peak at the rotational speed ω =94rad/s and then transitions to the next relatively stable motion stage with the increase of the rotational speed.

5. Conclusion

Taking the single progressing cavity pump as the research object, the dynamic model of rub-impact of fixed rotor system was established. When the speed reaches 32.2rad/s, the revolution radius of the rotor's rotary center reaches the minimum, the vibration of the rotor is the most violent and the motion is extremely unstable. When the speed continues to increase to 62.4rad/s, the rubbing contact between stator and rotor reaches the most stable state and the motion between stator and rotor is more like the pure rolling around the stator's inner surface. As the rotating speed continues to increase, the rotor becomes unstable again.

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