Design and application of eccentric balance flexible pumping unit

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Abstract. In the light of the problems of multi-transmission segments, poor movement performance, big volume and weight, large fluctuating range of payload, negative power and torque of beam pumping units, the principle of eccentric balance was suggested, eccentric rotating mechanism is adopted to change the interval of upstroke and down stroke, positive torque with alternating uniformly, energy saving and high efficiency were realized. Basing on the setting up motion and dynamic models of eccentric flexible pumping unit, the motion and dynamic characteristic was analyzed. Field test demonstrated that positive torque can be realized completely, the installed power is decreased 80% and the weight of whole prototype is decreased 25%, system efficiency is improved from 14% to 24.3%, electricity saving reached to more than 50%.

1. Introduction
Conventional beam pumping units have always occupied the leading position of rod pumping equipment, but due to unreasonable structure, there are a variety of problems [1-4]: many energy transfer links, poor performance, large volume and weight, the output shaft torque of reducer varies greatly and has negative value. Therefore, the eccentric balance theory was proposed and the eccentric flexible pumping unit [5-7] was developed. The transfer links were reduce by replace the flexible chain instead of four-link mechanism, and the operating range of the upper and lower stroke of the suspension load was changed by eccentricity rotary mechanism, so that the torque load of the motor and reducer can be kept within the positive range with alternating uniformity, and the purpose of energy saving and high efficiency can be achieved.

2. Structure and principle of eccentric balance pumping unit
Eccentric flexible pumping unit is mainly composed of balance system and energy transfer system, as shown in figure 1. As shown in figure 2, 3, eccentric balancing mode is relative to concentric balance. Eccentric flexible pumping unit adopts double crank linkage and double rotating center structure. That is, one crank drives the balance weight and links the other crank which drives the load of the oil well, both cranks rotate counter clockwise around their respective center. The work range of polished rod load was changed, while the upper stroke interval of oil well load became larger and the lower stroke interval became smaller. The negative value of net torque obtained by superposition with the balance weight torque becomes positive and the peak value decreases, so as to achieve the effect of positive torque and uniform torque throughout the cycle.
The main working principle of the eccentric flexible pumping unit is roughly similar to that of the flexible double-stroke pumping unit. The power of the eccentric flexible pumping unit starts from the fixed node B through the flexible rope, by passes the moving pulley A, the fixed pulley C and D and connects the pumping pump directly from the wellhead. The four-link mechanism was improved, the transmission link was simplified, and the energy loss was reduced. In the same stroke condition, the eccentric flexible pumping unit is smaller in volume and less in material consumption than the conventional beam pumping unit. And the beam travelling mechanism is cancelled, which will reduce the weight of the pumping unit, so as to improve the performance of the operation, reduce energy consumption.

3. Kinematics and dynamics calculation of eccentric flexible pumping unit

3.1. Kinematics analysis

As shown in figure 2, the crank radius O'A of the movable pulley is r, and the rotary center O' of the movable pulley is located between the fixed pulley B and C. The horizontal distance between O' and B is a, while the vertical distance is b. The balance weight crank is R. The crank angle of the movable
pulley is \( \theta \) at any time, and the corresponding balance weight crank Angle is \( \alpha \). The radius of the movable pulley is ignored for simplify the calculation. The following formula can be obtained from the geometric relationship \([8-14]\):

\[
AB = \sqrt{(a - r \sin \theta)^2 + (b - r \cos \theta)^2} \quad (1)
\]

\[
AC = \sqrt{(a + r \sin \theta)^2 + (b - r \cos \theta)^2} \quad (2)
\]

Therefore, the suspension displacement \((S)\) at any time is:

\[
S = (AB + AC) - 2\sqrt{a^2 + (b - r)^2} = \sqrt{(a - r \sin \theta)^2 + (b - r \cos \theta)^2} + \sqrt{(a + r \sin \theta)^2 + (b - r \cos \theta)^2} - 2\sqrt{a^2 + (b - r)^2} \quad (3)
\]

Calculate the first and second reciprocal of the above formula. It can be concluded that the suspension velocity \((v)\) and acceleration \((a)\) are:

\[
v = \frac{dS}{d\theta} = \frac{br \sin \theta - ar \cos \theta}{\sqrt{a^2 + b^2 + r^2 - 2ar \sin \theta - 2br \cos \theta}} + \frac{ar \cos \theta + br \sin \theta}{\sqrt{a^2 + b^2 + r^2 + 2ar \sin \theta - 2br \cos \theta}} \quad (4)
\]

\[
a = \frac{dv}{d\theta} = \frac{ar \sin \theta + br \cos \theta}{\sqrt{a^2 + b^2 + r^2 - 2ar \sin \theta - 2br \cos \theta}} + \frac{(br \sin \theta - ar \cos \theta)^2}{(a^2 + b^2 + r^2 - 2ar \sin \theta - 2br \cos \theta)} + \frac{br \cos \theta + ar \sin \theta}{\sqrt{a^2 + b^2 + r^2 + 2ar \sin \theta - 2br \cos \theta}} + \frac{(ar \cos \theta + br \sin \theta)^2}{(a^2 + b^2 + r^2 + 2ar \sin \theta - 2br \cos \theta)} \quad (5)
\]

3.2. Dynamic analysis
The movable pulley of eccentric balance pumping unit is taken as the research object, and its force analysis is shown in figure 4.

![Figure 4. Force analysis diagram on movable pulley](image)

Ignoring the influence of rotation speed change on the tension of flexible rope, and the tension of flexible rope on both sides of the movable pulley is considered to equal, so the force on the movable pulley is synthesized as follows:

\[
F = \sqrt{2P^2[1-\cos(\alpha_1 + \alpha_2)]} = 2P \sin \frac{\alpha_1 + \alpha_2}{2} \quad (6)
\]
\[ \beta = \frac{\pi}{2} - \alpha_1 - \frac{\pi - \alpha_1 - \alpha_2}{2} = \frac{\alpha_2 - \alpha_1}{2} \]  

(7)

Where, \( P \) is the tension of the flexible rope, it is the load of the suspension point; \( \alpha_1 \) and \( \alpha_2 \) are the angle between the flexible rope and the horizontal direction.

Figure 5: Motion and force diagram of eccentric balance pumping unit

Figure 5 shows the motion and force diagram of eccentric balance pumping unit. In the triangle \( O_2O_3O_4 \):

\[ O_2O_3 = e ; \quad O_2O_4 = L_3 \]  

(8)

\[ \angle O_2 = \alpha_3 = \frac{\pi}{2} - \tau - \theta_1 \]  

(9)

From the cosine theorem, we can get:

\[ L_5 = O_5O_4 = \sqrt{e^2 + L_3^2 - 2el_3 \cos \alpha_3} \]  

(10)

In the triangle \( O_5O_3O_4 \), the following formulas can be obtained from the cosine theorem:

\[ \alpha_4 = \angle O_5O_3O_4 = \arccos \frac{R^2 + L_3^2 - L_4^2}{2RL_3} \]  

(11)

\[ \alpha_5 = \arcsin \frac{e \sin \alpha_3}{L_5} \]  

(12)

According to the geometric relationship in figure 4, it can be concluded that:
\[ \alpha_4 = \angle O_3O_4 = \arccos \frac{R^2 + L_5^2 - L_4^2}{2RL_4} \]  

(13)

Where, \( \theta_1 \) is the crank angle of balance weight, \( \theta_2 \) is the crank angle of movable pulley.

### 3.3. Calculation of crank shaft torque

The force exerted on the crank in the working process of the eccentric balance pumping unit is showed in figure 5. The torque \( M \) of the output shaft \( O_2 \) of the reducer is the difference between the oil well load equivalent torque \( M_o \) and the balance weight equivalent torque \( M_w \), that is:

\[ M = M_o - M_w \]  

(14)

As can be seen from the figure:

\[ M_o = F_{45} \cdot \overline{O_2N} \]  

(15)

According to the geometric relationship in the figure and the force balance at point \( O_5 \), the following equation can be obtained:

\[ F_{45} = \frac{F \sin(\theta_2 - \beta)}{\sin \alpha_6} \]  

(16)

\[ \overline{O_2N} = L_3 \sin \angle O_2O_4O_5 = L_3 \sin(\pi - \alpha_4 - \alpha_6 + \alpha_5) \]  

(17)

\[ \alpha_6 = \angle O_3O_4 = \arccos \left( \frac{R^2 + L_5^2 - L_4^2}{2RL_4} \right) \]  

(18)

The torque of the balancing weight acting on the output shaft \( O_2 \) of the reducer can be calculated as following:

\[ M_w = G_2 \cdot L \cdot \sin(\theta_1 + \gamma) \]  

(19)

Where, \( G_2 \) is the weight of balance block, N; \( L \) is the length of balance weight crank, m; \( \gamma \) is the offset angle, °.

### 4. Calculation examples

The eccentric flexible pumping unit is adopted. The parameters of the oil well are as follows: pumping speed 4min⁻¹, crank radius 1m, the downhole pump depth 1000m, submergence zero, pump diameter 44mm, sucker rod diameter 22mm, linear density 3.07kg/m, liquid weight 8722N/m³, elastic modulus 2.1GPa. Figure 6 shows the output shaft torque curve of the reducer of the pumping unit through calculation.
Figure 6. The suspension point motion curves of eccentric balance pumping units

According to the calculation examples, the suspension point motion curves of eccentric balance pumping units is shown in Figure 6, it can be seen from the figure 6, the biggest displacement of the suspension point is 2.12m, the maximum speed is 0.443m/s, the maximum acceleration is 0.186m/s². These data illustrates the good movement characteristic for the eccentric balance pumping units.

Figure 7. Torque curves of eccentric balance pumping units

It can be seen from the figure 7, as the eccentric value exists between the rotary center of the movable pulley and the rotary center of the balance crank, the range of positive and negative torque at the suspension point has changed. After being balanced by the counterweight, the maximum torque is only 10187N/m, the minimum torque load is increased to 712N/m from the negative value of the beam-pumping units, and the torque load is alternately homogenized and positive. The pumping unit transmission performance and the motor utilization rate were increased. It is conducive to energy saving and the selection of low-power reducer and motor.

5. Field application

Figure 8. Eccentric flexible pumping unit photo in oil field application
As shown in Figure 8, field application was carried out in a production well of Daqing Oilfield in August 2018. Original beam pumping unit type used in this production well was CYJ6-2.5-26HB, and the production well parameters are shown in table 1 and table 2.

| Table 1. Working parameters of oil well |
|----------------------------------------|
| Well depth (m) | Pump diameter (mm) | Stroke (m) | Pumping speed (min⁻¹) | Submergence (m) | Theoretical displacement (m³/d) |
|----------------|---------------------|-----------|------------------------|-----------------|-------------------------------|
| 880            | 38                  | 2.5       | 4                      | 60.13           | 16.3                          |

| Daily liquid production (t/d) | Daily oil production (t/d) | Water cut (%) | Tubing pressure (MPa) | Casing pressure (MPa) |
|------------------------------|-----------------------------|---------------|-----------------------|----------------------|
| 5.44                         | 0.6                         | 89.15         | 0.46                  | 0.42                 |

| Table 2. Contrasting data of testing result |
|--------------------------------------------|
| Type                         | Stroke (m) | Pumping speed (min⁻¹) | Pump diameter (mm) | Maximum/Minimum torque (kN·m) |
|------------------------------|-----------|-----------------------|-------------------|-------------------------------|
| Eccentric pumping unit       | 2.5       | 4                     | 38                | 25/7                          |
| Installed power (kW)         |           |                       |                   |                               |
| Whole unit weight (t)        |           |                       |                   |                               |
| Power consumption per ton of liquid (kW·h) | |                   |                   |                               |
| System efficiency (%)        |           |                       |                   |                               |
| Beam pumping unit            | 2.5       | 4                     | 38                | 65/-15                       |
| Installed power (kW)         | 15        | 9                     | 3.3               | 14                            |
| Whole unit weight (t)        |           |                       |                   |                               |
| Power consumption per ton of liquid (kW·h) | |                   |                   |                               |
| System efficiency (%)        |           |                       |                   |                               |

The installed power of the eccentricity flexible pumping unit is 80% lower than that of the original beam pumping unit, and the weight of the whole unit is reduced by 25%. The output shaft of the reducer can fully achieve positive torque, the motor is always in the state of doing positive work, and the balance effect is remarkable. Through the comparative test of power consumption, the power consumption per ton of liquid decreased from 3.3 degrees to 1.5 degrees, the system efficiency increased from 14% of the original type to 24.3%, and the energy saving rate reached more than 50%.

6. Conclusion
(1) The eccentric balance theory was proposed, and the eccentricity rotary mechanism was used to change the operating range of the upper and lower stroke of the suspension load, so as to achieve the goal of energy saving and high efficiency by keeping the torque within the positive range and alternating homogenization.

(2) The kinematics and dynamics model of the eccentric flexible pumping unit were established, and the kinematics and dynamics analysis were carried out. The structural parameters of the whole unit were optimized based on the random direction method. After optimization, the maximum acceleration of the suspension point was reduced by 15.6%, the peak torque was reduced by 15.7%, and the root-mean-square torque was reduced by 18.5%. Therefore the dynamic performance is improved.

(3) Field test shows that the machine can fully achieve positive torque, compared with the original well conventional machine, beam pumping unit installed power is reduced by 80%, the weight of the whole machine is reduced by 25%, the system efficiency is increased from 14% of the original model to 24.3%, and the energy saving rate is more than 50%.
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