International Journal of Mechanical and Electrical Engineering
ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 2, Number 1, Year 2024
DOI: https://doi.org/10.62051/ijmee.v2n1.04
Journal homepage: https://wepub.org/index.php/IJMEE/index

Design and Analysis of Harmonic Drive Reduction Pump Jack for Dynamic Performance in Oil Extraction

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ABSTRACT

The purpose of this study is to provide a high gear ratio reducing pump jack system, utilizing the characteristics of high transmission ratio and precision of harmonic drives, in order to improve the efficiency of low-permeability oil field extraction. A comparison was made between the new system and the conventional walking beam pump jack. The results showed that at a stroke length of 1.5 m and pumping frequencies of 4.5 min^{-1}, 3.5 min^{-1}, 2.5 min^{-1}, 1.5 min^{-1}, and 0.5 min^{-1}, the maximum acceleration of the suspended load in the harmonic reducing pump jack was reduced by 20.79% compared to the conventional walking beam pump jack.

KEYWORDS

Pump Jack; Harmonic Drive Reducer; Low-permeability Oil Field; Maximum Acceleration; Motion Performance.

1. INTRODUCTION

In recent years, the exploitation of low permeability oilfields has become the focus of many scholars. Among the proven reserves in China, the proportion of low permeability reservoir reserves is very high, accounting for more than 2/3 of the national reserves. The beam pumping unit [1] has the advantages of simple structure and large transmission power, and has been widely used in oil exploitation. However, in the face of oilfields with a permeability of (1.1~10.0) ×10-3μm2, there are low working efficiency and high energy consumption [2] problems. Obviously, reducing pumping unit strokes is an important way to achieve higher efficiency and lower energy consumption.

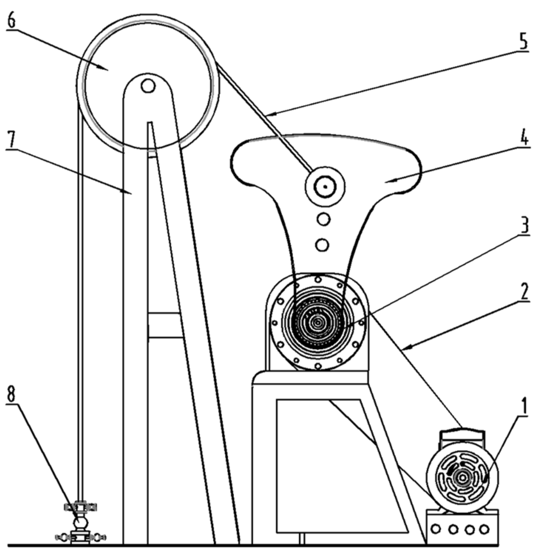
Among them, the early work was mainly to improve the existing pumping unit. The research of Wu Junfei et al. [3] and Liu Yongping [4] showed that the modification of the CYJY10-4.2-53HF pumping unit, the completion of the crank automatic balance and the improvement of the drum pumping unit can achieve the purpose of stable pumping operation and energy saving. With the deepening of research work, scholars began to study and design new pumping units. Shao Jun et al. [5], Yi Huicheng et al. [6], Cao Zhongliang et al. [7] designed a new energy-saving pumping unit with the reversing mechanism of the pumping unit as a breakthrough. Change the motion characteristics of the pumping unit, so as to adapt to the oil wells with different well conditions, and achieve the purpose of energy saving and emission reduction. The survey literature found that the reduction of pumping unit stroke mainly focused on the improvement of the original pumping unit and the design of new pumping units, while few scholars focused on changing the pumping unit deceleration mechanism. Among them, Peng Zhenhua et al. [8] conducted a mechanical analysis of the gear-long annular rack and pinion transmission mechanism, which showed that the force of the transmission mechanism changed with the position of the gear during the commutation process, but the specific change law was not quantitatively explained.

According to the research of the reducer mechanism, conventional reducers such as cylindrical gear reducer have a single-stage reduction ratio of (1-5) and a two-stage reduction ratio (3-30), a worm gear and worm reducer with a reduction ratio of (8-80), a bevel gear single-stage reduction ratio (3-6) and a two-stage reduction ratio (10-50), all of which cannot meet the needs of the pumping unit for low stroke. It is found that the transmission ratio of the harmonic reducer reaches (50-500) and has the characteristics of small size and high transmission accuracy [9], a new pumping unit scheme based on harmonic reducer is designed and the kinematic analysis of this scheme is carried out.

2. TECHNICAL ANALYSIS

2.1. Harmonic Deceleration Pumping Unit Structure

The pumping unit structure harmonic deceleration pumping unit is mainly composed of power mechanism, transmission mechanism and reversing balance mechanism. As shown in Figure 1, the power part is made up of an electric motor; The transmission part is mainly composed of V-belt and harmonic reducer; The commutation part is mainly composed of a crank. The power is output by the motor to the V-belt, and the wave generator is input to the harmonic reducer through the V-belt, and the deceleration is completed under the action of the flexible wheel and the steel wheel. Finally, the power is output to the crank, and the crank converts the rotary motion into linear reciprocating motion, so as to complete the reversal of the pumping unit and realize the oil recovery operation.



1-Motor; 2-V belt; 3-harmonic reducer; 4 - crank with counterweight; 5-a flexible piece;

6-rope sheave; 7-frame;8- Christmas tree.

Figure 1. Schematic diagram of the structure of the harmonic deceleration pumping unit

2.2. Basic Size Calculations

As can be seen from Figure 2, the stroke of the pumping unit and the radius of the crank should be the same. It starts counterclockwise from point D and reaches the maximum displacement at point E. The length of the crank is half of the working stroke.

It can be solved by geometric relations

$$BF = \frac{S \cdot (2 \cdot AF - S)}{2 \cdot [AF \cdot \cos(\alpha) - AF + S]} \tag{1}$$

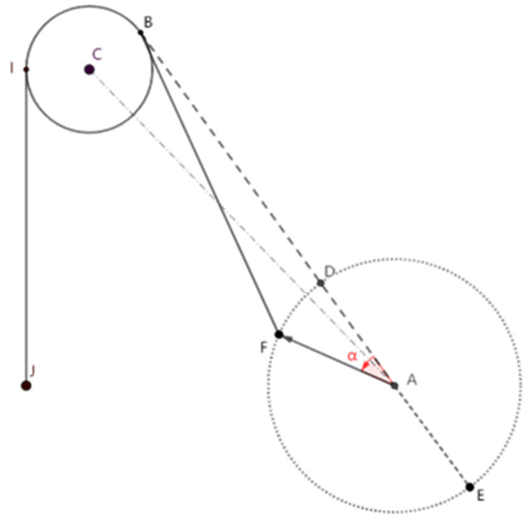


Figure 2. The schematic diagram of the harmonic deceleration pumping unit

where: is the displacement of the application point, m; AF is the length of the crank, m; is the angle at which the crank turns, rad/s.

3. MOTION ANALYSIS

The motion law of pumping unit is the basis of pumping unit dynamics , and it is also the core of the comprehensive evaluation of pumping unit technology and performance . Its motion characteristics and dynamic performance parameters mainly include suspension displacement, velocity and acceleration. Among them, acceleration affects the suspension dynamic load, which is the most important parameter .

3.1. Motion Characteristic Parameters

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3.2. Motion Characteristic Parameters

The schematic diagram of the harmonic deceleration pumping unit mechanism is shown in Figure 2. In Fig. 2, AD is the position of the crank when the suspension point of the pumping unit is at the lowest point, and this position is the starting position; Then AE is the position of the crank when the suspension point of the pumping unit is at the highest point. Figure 2 shows that:

$$\alpha = \omega t \tag{2}$$

where: is the angle at which the crank AF turns counterclockwise from the starting position, rad; ω is the crank speed, rad/s; t is the time taken from the starting position to turn the angle of the crank AF, s.

3.2.1. Dangling Displacement

Starting from the starting position AD, the displacement St of the overhang when turning the angle α can be expressed as:

$$S_t = AF + FB - AB \\ = AF + \sqrt{(AF^2 + AB^2 - 2 \cdot AF \cdot BF \cdot \cos\alpha)} - AB \tag{3}$$

where: AF is the radius of rotation of the crank, m; BF is the length of the wire rope used from the crank to the rope pulley, m; AB is the tangent length from the center of the crank to the rope sheave, m.

3.2.2. Overhang Velocity

The suspension velocity at any time can be derived from the suspension displacement St against time t:

$$v_t = \frac{dS_t}{dt} \tag{4}$$

3.2.3. Suspension Acceleration

The overhang acceleration at any moment can be changed by the overhang velocity to the time t derivation:

$$a_t = \frac{dv_t}{dt} = \frac{dS_t}{dt^2} \tag{5}$$

4. INSTANCE COMPUTING

The suspension acceleration of the pumping unit is an important part of the suspension point load, and the lower acceleration has a favorable effect on the pumping unit. In this section, it will be calculated that when the stroke is 1.5 m, the strokes of the conventional beam pumping unit and the harmonic reduction pumping unit are 4.5 min^{-1}, respectively. 3.5 min^{-1}; 2.5 min^{-1}; 1.5 min^{-1}; The acceleration at 0.5 min^{-1} was plotted for comparative analysis.

4.1. Initial Parameters

Taking the working well parameters of a pumping unit in an oilfield as a reference, the mechanism parameters are shown in Table 1.

Table 1. Dimensions of CYJ- CYJ-6-1.5-37 Conventional Oil Pump Mechanism

Forearm of the beam A	Beam hind arm B	Connecting rod I	Crank R
3000 mm	2400 mm	3350 mm	1150 mm

4.2. Calculation Results

By substituting the initial parameters into Eq. (2), Eq. (3) and Eq. (4), the acceleration of the pumping unit can be obtained, and the drawing curve is shown in Fig. 3 and Fig. 4.

It can be seen from Fig. 3 that with the increase of the stroke, the suspension acceleration of the pumping unit increases, the lower the stroke, the more gentle the acceleration curve of the pumping unit, the more stable the operation of the pumping unit, and the acceleration curve is roughly symmetrical with respect to RAD. The absolute values of the maximum and minimum accelerations are equal for the same stroke; The acceleration reaches its maximum at 0 rad (the moment when the bottom dead center moves upward) and rad (at the top dead center position). The acceleration stroke and maximum acceleration of the harmonic deceleration pumping unit are shown in the first and second columns of Table 2.

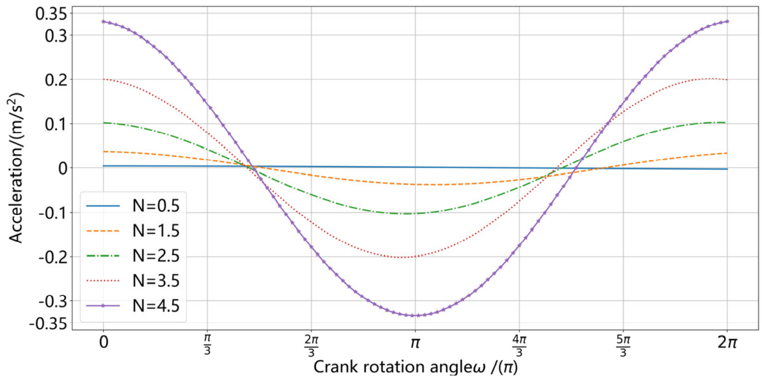

Figure 3. Harmonic Drive Pump Suspension Point Motion Characteristics Curve

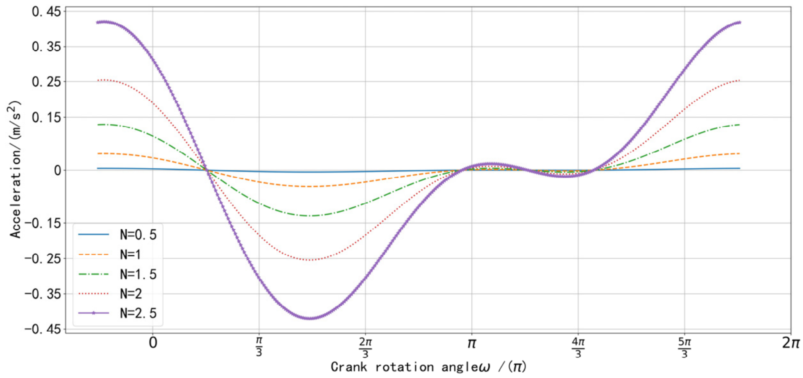

Figure 4. Harmonic Drive Pump Suspension Point Load

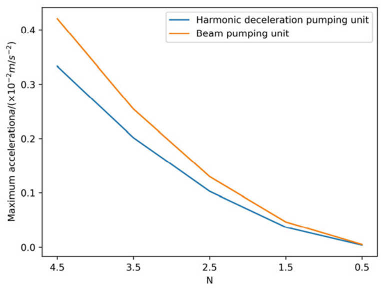

Figure 5. Curve of Maximum Acceleration for Two Different Oil Pumps under Identical Operating Conditions

It can be seen from Figure 4 that with the increase of the stroke, the suspension acceleration of the pumping unit increases, the lower the stroke, the more the acceleration curve of the pumping unit becomes more gentle, and the pumping unit runs more smoothly; At 0 rad (the moment the bottom dead center moves upwards) and $\frac{\pi}{2}$ rad when the acceleration reaches its maximum, respectively. The acceleration stroke and maximum acceleration of the harmonic deceleration pumping unit are shown in the first and third columns of Table 2.

The fourth column of Table 2 calculates that the stroke of the harmonic deceleration pumping unit and the traveling beam pumping unit is 4.5 min-1 when the stroke is 1.5 m. 3.5 min-1; 2.5 min-1; 1.5 min-1; The reduction rate of the maximum acceleration at 0.5 min-1 shows that the harmonic deceleration pumping unit is 20.79% lower than that of the beam pumping unit.

Table 2. A Comparison of Maximum Acceleration of Two Different Oil Pumps under Identical Operating Conditions

Pumping unit N/(min^{-1})	Harmonic deceleration a/(m/s^2)	Regular a/(m/s^2)	Reduction rate (%)
N=4.5	0.333099	0.420545	20.79
N=3.5	0.201504	0.254404	20.79
N=2.5	0.102808	0.129798	20.79
N=1.5	0.037011	0.046727	20.79
N=0.5	0.004112	0.005192	20.79

In order to compare the maximum acceleration of the two pumping units under the same working conditions more intuitively, Figure 5 is drawn using the data in Table 2. As can be seen from the figure, when the strokes are both 1.5 m, the maximum acceleration of the two pumping units decreases with the decrease of the stroke, and this reduction time is nonlinear. Under the same stroke, the maximum acceleration of the suspension points of the harmonic deceleration pumping unit is smaller than that of the floating beam pumping unit.

5. CONCLUSION

(1) According to the characteristics of low permeability oilfield, a large transmission ratio reduction pumping unit was designed.

(2) When the stroke is 1.5 m, the strokes of the conventional beam pumping unit and the harmonic reduction pumping unit are calculated to be 4.5min^{-1}, respectively. 3.5 min^{-1}; 2.5min^{-1}; 1.5 min^{-1}; The acceleration at 0.5 min^{-1} was plotted, and the maximum acceleration of the suspension point of the harmonic deceleration pumping unit was found to be 20.79% lower than that of the conventional beam pumping unit, and the inertial load was smaller in motion, and the operation was more stable.

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