Self-Balanced Double Horse Head and Rack-And-Pinion Driven Pumping Unit Based on Intermittent Power Supply Control

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Abstract. Considering the shortcomings of beam pumping unit, a kind of mainstream equipment serving in oilfields of China today, also known as “Kowtow Machine”, such as high energy consumption, low efficiency and disturbance caused to grid, a self-balanced double horse head rack-and-pinion driven pumping unit based on intermittent power supply control is put forward by combining the rack and pinion drive with offset crank slider with intermittent power supply motor control. This unit has the following features: (1) having the quick-return characteristics compared with the existing centric mechanism, i.e. slow move during travel under heavy load, and quick return during travel under light load, which are suitable for pumping unit; (2) utilizing the stable drive through rack and pinion, and employing the double horse head structure to keep the vertical downward force applied by counterweight to beam. Moreover, the counterweight is self-balanced, and receives no additional torque at both ends, so as to improve the force applied to beam; (3) using the microcontroller to control the start and stop of motor, which lowers the loss of motor and its power supply system, so as to reduce the consumption of electric power and enhance the utilization rate of equipment. Additionally, pumping unit is disconnected from grid when it is under no load, in order to reduce the impact on and disturbance caused to grid. We have: (1) completed the structural design of this product, which realizes the energy conservation by around 49.52% compared to the conventional beam pumping unit; (2) finished the prototype of the product after conducting a lot of work including mechanical analysis and design, Solidworks 3D modelling and AutoCAD 2D drafting, Simulink simulation, fabrication, assembly and commissioning; (3) performed the test to verify that the power of the prototype is basically consistent with that in the theoretical analysis, which preliminarily meets the expectation; (4) generalized the prospects on the future application and improvement scheme of this product.

1. Background and Significance of the Research
At present, “Kowtow Machine”, the major oil extraction equipment serving in the oilfields of China, employs the crank-rocker mechanism to drive the vertical reciprocating movement of sucker rod, and pump the oil out of well to the ground. However, it mainly has the following shortcomings: poor efficiency; high energy consumption; and disturbance caused to grid. In most areas of China, beam pumping unit has an average efficiency of 12%-23%, which has never exceeded 30% in some well-
developed areas. Hence, it is especially significant to design an energy-saving and practical self-balanced pumping unit.

2. Structure and Work Principles
A sketch of its structure is shown in Fig. 1.

![Figure 1. Self-balanced double horse head rack-and-pinion driven pumping unit](image)

The work process is as follows: at both ends, beam 3 has primary horse head 2 connected to sucker rod and load 1, and secondary horse head 5 connected to beam 3. Bearing seat 4 is fixed at the middle of beam 3. Secondary horse head 5 is matched with railcar driving rack (slider) 6, which is fixed onto the rail 7. Counterweight 8 is connected nearby through wire rope. The pivot of drive system 11 is offset from slider 6, and quick-return characteristics are generated thanks to the existence of offset distance e. The transmitted force drives the rotation of crank 10, which makes linkage 9 move and pump oil. A balanced structure is formed by beam 3, primary horse head 2, and secondary horse head with pinion 5, counterweight 8, and counterweight pulley. During the swing of beam, it can ensure unchanged direction of force, and automatically balance the torque all the time.

3. Performance Analysis

3.1. Performance Analysis of Mechanical Structure
It is assumed that primary horse head $G_1=14000\text{N}$, maximum weight of pumped oil $F_{\text{max}}=12000\text{N}$, counterweight $G_2=17000\text{N}$, and rotational speed $6\text{r/min}$.

![Figure 2. Analysis on load application](image)
On this basis, it is obtained that the velocity of primary horse head is \( V_1 = 0.59 \times \cos(3\theta) \) m/s.

It is assumed that \( \theta \) is positive when rod 2 rotates counterclockwise to the horizontal line, and \( \alpha \) is positive when rod 4 rotates counterclockwise to the horizontal line.

If the pumping quality has linear relationship with the swing angle \( \theta \), there is

\[
F(\theta) = \begin{cases} 
\frac{36000}{\pi} \times \theta + 6000, & \alpha \in \left[ \frac{7\pi}{12}, \frac{5\pi}{3} \right] \\
6000, & \alpha \in \left[ \frac{5\pi}{3}, \frac{12\pi}{12} \right] 
\end{cases} 
\]

(N), \( \theta \in \left[-\frac{\pi}{6}, \frac{\pi}{6} \right]

Hence, the power is

\[
P = V_1 \times (F(\theta) + G_i) - G_2 \times V_1 \times \frac{l_2}{l_1} \sin \beta = \frac{e + l_4 \cos \alpha}{l_3}
\]

\[
306 - l_4 \cos \alpha - \sqrt{l_3^2 - (e + l_4 \cos \alpha)^2} = l_2 \times (\frac{\pi}{6} + \theta)
\]

The torque is

\[
T = \frac{l_1}{l_2} \times (F(\theta) + G_i) - G_2 \times \frac{\cos(\alpha - \beta)}{\cos \beta} \times l_4
\]

The known values are substituted into the above equations to obtain the following results:

\[
\begin{align*}
\beta &= \arcsin\left(\frac{80 + 80 \times \cos \alpha}{236}\right) \\
\theta &= \frac{306 - 80 \times \sin \alpha - \sqrt{55696 - (80 + 80 \times \cos \alpha)^2}}{150} - \frac{\pi}{6}
\end{align*}
\]

Hence, the final relations of power and torque are as follows:

\[
\begin{align*}
\text{Power } P &= \begin{cases} 
0.59 \times \cos 3\theta \left(\frac{36000}{\pi} \times \theta + 3000\right) & \alpha \in \left[ \frac{7\pi}{12}, \frac{5\pi}{3} \right] \\
1770 \times \cos 3\theta & \alpha \in \left[ \frac{5\pi}{3}, \frac{31\pi}{12} \right]
\end{cases} \\
\text{Torque } T &= \begin{cases} 
\frac{\cos(\alpha - \beta)}{\cos \beta} \times \left(\frac{3264}{\pi} \times \theta + 272\right) & \alpha \in \left[ \frac{7\pi}{12}, \frac{5\pi}{3} \right] \\
272 \times \frac{\cos(\alpha - \beta)}{\cos \beta} & \alpha \in \left[ \frac{5\pi}{3}, \frac{31\pi}{12} \right]
\end{cases}
\end{align*}
\]

3.2. Simulation and Motor

Based on the above relations for power and torque, Simulink simulation is carried out for the pumping unit. Motor employs four types of control, i.e. star-connected winding, star connection and intermittent power supply, delta-connected winding, delta connection and intermittent power supply. The model is shown in the following figure:
The output powers under four types of motor control are compared as follows:

![Comparison of output powers under four types of control](image)

**Figure 4.** Comparison of powers under four types of control

In the above figure, during an oil extraction stroke:

- The average output power of motor is 5,058.77(W) for star-connected winding, 4,526.34(W) for star connection and intermittent power supply, 14,345.78(W) for delta-connected winding, and 14,193.84(W) for delta connection and intermittent power supply.

As revealed in the analysis, star-connected winding can save the energy by around 64.74% compared with delta-connected winding, while intermittent power supply can save the energy by around 10.53% if it is employed. Moreover, positive peak power does not vary significantly no matter whether intermittent power supply is employed, but intermittent power supply can prevent the power causing reverse power supply from motor to grid. Hence, star-connected winding and intermittent power supply is the optimal combination for energy conservation in the project.

### 3.3. Test Analysis

The improved model is tested to obtain the following results:

![Simulink model simulation](image)

**Figure 3.** Simulink model simulation
Table 1. Calculated powers based on measured currents and voltages

| α  | 0   | 45  | 90  | 135 | 180 | 181 | 225 | 270 | 315 | 359 | 360 |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| P1/W | 299.8 | 311.5 | 319.2 | 321.9 | 368.3 | 0   | 0   | 0   | 0   | 298.3 |
| P2/W | 603.4 | 668.8 | 478.3 | 860.1 | 1264.6 | 1264 | 469.2 | 405 | 602.97 | 603.4 |

The pumping unit in service is compared with the improved model in terms of power as shown in the following figure:

![Comparison of powers between beam pumping unit and double horse head pumping unit](image)

**Figure 5.** Comparison of powers between beam pumping unit and double horse head pumping unit

As shown in the analysis, the power of the improved model is significantly lowered compared with the pumping unit in service. Moreover, the power varies steadily, so the power consumption within one stroke decreases significantly. Additionally, intermittent power supply is employed for motor control to ensure zero power consumption during power failure, so as to fulfill the objectives of energy conservation.

4. Design of Scale Model

4.1. Determination of Main Parameters

During the process of scale model design, we selected that 3 pinion modules with the radius of 150mm (which is also the length $L_2$) and the swing angle of $\pi/3$, and determined that the length of crank $L_4$ was 80mm. Based on the lengths of rack and crank, we concluded that the length of linkage was 236mm, and the length at the other end of beam $L_1$ was 170mm. The offset distance $e$ at the offset part was 80mm, while the distance from the center of crank to the center of beam was 194.2mm. In the actual processing, we may increase some lengths properly to facilitate fabrication and installation.

We selected BS57HB51-03 stepping motor, and used Arduino Uno r3.4.2 microcontroller.
5. Strength Verification of Rack and Pinion

5.1. System Power
The maximum power of pumping process (under load) is \( P = F \times V \).

When \( F = 15000 \) N, and \( V_1 \) is 0.42 (m/s), \( P = 15000 \times 0.42 = 6300 \) (W)

Hence, the torque is \( T = \frac{955000 \times 6.3}{6} = 99750 \) (N\( \cdot \)mm).

In which, \( n \) is the rotational speed, and its unit is r/min.

5.2. Selection of Design Parameters and Allowable Stress for Pinion Drive
According to the mechanical principles, it is learned that:

1. Selection of pressure angle \( \alpha \): China stipulates that the standard pressure angle of pinion drive for general purpose is \( \alpha = 20^\circ \).

2. Selection of modules \( m \) and teeth \( z \): The number of modules is 3. To prevent the undercutting of pinion, \( z \) should be \( \geq 17 \) for the standard spur gear with \( \alpha = 20^\circ \). In this case, \( z = 100 \).

3. Selection of tooth thickness \( b \) and diameter \( d \): Take \( b = 30 \) mm, and \( d = 300 \) mm.

4. The strength of pinion is verified as follows:

\[
\text{Load: } P = 6.300 \text{W, } T = 99.750 \text{N} \cdot \text{mm}
\]

Use factor 1.1, dynamic load factor 1.0, tooth thickness load distribution factor 1.0, axial load distribution factor 1.1, i.e. \( K = K_a K_f K_r K_i = 1.1 \times 1 \times 1 = 1.21 \)

Bending fatigue limit: \( [\sigma_f] = 896 \text{MPa} \)
Contact fatigue limit: \( [\sigma_c] = 583 \text{MPa} \)
For bidirectional operation, it is multiplied by 0.7, so \( \sigma_{B} = 408.3 \text{MPa} \)

Form factor \( Y_F \) = 2.2, and stress correction factor \( Y_S \) = 1.82

Conclusion: Pinion strength satisfies the requirements
6. Economic Analysis
We used MATLAB to draft the power comparison curves between the conventional beam pumping unit and the self-balanced double horse head rack and pinion driven pumping unit, as shown in the following figure:

![Power comparison between beam and double horse head pumping units](image)

**Figure 7.** Power comparison

As revealed in the analysis, during an oil extraction stroke:

1. The average output power of beam pumping unit is 6,856.21(W), while the average output power of double horse head pumping unit is 3,461.10(W), so the latter can save the energy by around 49.52% compared with the former;

2. The peak power of beam pumping unit is 5,362(W), while the peak power of double horse head pumping unit is 2,578(W), so the output power of double horse head pumping unit is relatively steadier than that of beam pumping unit, which reduces the impact on grid.

7. Innovations
This product has several innovations as follows:

1. More reasonable structure: (1) with regard to mechanical principles, offset crank slider mechanism is employed to realize higher efficiency. Compared with the existing centric mechanism, it has the quick-return characteristics, i.e. slow move during travel under heavy load, and quick return during travel under light load, which are suitable for pumping unit; (2) according to the mechanics of materials, double horse head structure keeps unchanged direction of force applied by counterweight to beam, that is, vertical downward force, which is similar to the load force, so it improves the force applied to beam;

2. Lower consumption of motor and its power supply system and disturbance caused to grid, and improved utilization rate: (1) the drive of motor relies on intermittent power supply, which can reduce all the power losses and considerably lower power consumption under no load and during power generation, as it adaptively judges and selects the best time of power connection and disconnection; (2) pumping unit is disconnected from grid under no load to lower the impact on and disturbance caused to grid; (3) during power disconnection, potential energy is converted into kinetic energy, which is stored in the rotation of counterbalance in the pumping unit. During operation of motor, kinetic energy is released to drive the load in place of power supply for a certain period. Hence, it can save the electric power needed to increase the work of load during the period, so as to achieve better energy conservation; (4) beam counterweight is self-balanced, and there is not additional torque at both ends, so the original output of motor is not affected;

3. Safe, reliable, practical, and economical: (1) stable operation with rack and pinion drive; (2) microcontroller to control the start and stop of motor automatically.
8. Significance and Application Prospects

(1) The design, development, promotion and application of energy-saving pumping unit are safe, reliable, practical and economical.

(2) It is an inevitable trend to develop and apply energy-saving pumping unit. Compared with the conventional pumping unit, the improved design proposed in this paper utilizes the offset rack and pinion drive, and employs the microcontroller to control the start and stop of motor automatically, so as to effectively lower the power losses of motor and its power supply system, and realize energy conservation.

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