Crank modification of direct drive beam pumping unit based on analysis of dynamics and balance mechanism

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Abstract. In view of the problems existing in the power end drive mechanism of conventional beam pumping units, the power end drive mechanism has been improved through optimized design. Abandon the belt and gearbox and replace it with a crankshaft and universal coupling, which can increase the motor torque and improve the transmission efficiency of the system. The asynchronous motor is changed to a permanent magnet synchronous composite motor, which realizes direct drive, low speed and large torque, and reduces the energy consumption and failure rate of the whole machine. Based on the dynamics and balance mechanism, the multi-body dynamics analysis of the pumping unit is carried out.

1. Introduction
At present, most of the pumping units used in land oil fields in China are still traditional beam pumping units. The traditional beam pumping unit has a complex structure and low efficiency. The motor drive needs to be output through a multi-stage reduction box and a linkage mechanism. The overall efficiency of the system is about 30%.

For conventional beam pumping unit, its belt, pulley and gear box are easily damaged, resulting in oil wells shut down, seriously affected the normal operation of the oil fields of work, it has become a problem for most oil field to be solved. Among them, the pros and cons of power performance directly affect the extraction effect of crude oil. In order to better improve the oil recovery efficiency of the pumping unit and reduce energy consumption, improvements are made on the basis of the traditional beam pumping unit. Abandon the Gear box and belt drive means, they are replaced by a high-torque low-speed direct-drive permanent magnet synchronous motor.

Although the direct-drive beam pumping unit has changed the power transmission chain length and low transmission efficiency of the traditional beam pumping unit, the following problems still exist in the actual oil field use of the direct-drive beam pumping unit. The main questions:

a). Since the motor direct drive crank four-bar linkage, resulting in direct drive permanent magnet synchronous motor is a significant increase in the number of turns. In order to meet the requirements of lower strokes, it is necessary to combine frequency conversion and increasing the number of turns of the motor, which leads to an increase in the cost of motor manufacturing and the complexity of the control system.

b). Direct drive by permanent magnet synchronous motor, the suspended load and counterweight of the pumping unit will cause large torque problems on the motor output shaft Cause the output shaft of
the motor to bear a large impact load, in addition torque during the operation of the four agencies have
greater volatility, or even a negative torque occurs.

In this paper, direct-drive machine beam pumping unit for multi-body dynamics analysis based on
kinetics and equilibrium mechanism. Systematic analysis of three balancing methods for direct-drive
beam pumping units. Designed three transformation schemes: Crank balance, beam balance, compound
balance, and the calculation and comparative analysis of these three schemes are carried out. The direct
drive beam pumping unit is the research object, The virtual prototype model of the direct-drive beam
pumping unit is established by using the automatic analysis software of mechanical system dynamics
ADAMS, A simulation test was carried out, combined with the actual situation of the pumping unit, and
the analysis found that the crankshaft after the transformation had increased transmission arm and
transmission torque, which effectively reduced the torque pressure on the crankshaft.

2. Basic principle of direct drive beam pumping unit
The direct-drive beam pumping unit is a new type of oil extraction equipment with good transmission
performance and low energy consumption. Its working principle is the permanent magnet synchronous
motor as power source, and pass it to the crank, and transmitted to the crank, the crank drives the four-
bar linkage mechanism, which converts the rotary motion of the permanent magnet synchronous motor
into the upward and downward linear reciprocating motion of the donkey head, and finally the donkey
head drives the sucker rod to make a piston reciprocating motion, and finally realizes the oil production
work of the oil well. As shown in Figure 1 below, it is a schematic diagram of the structure of the direct
drive pumping unit

![Figure 1. Schematic diagram of direct drive beam pumping unit structure.](image)

1- Base  2- Permanent magnet synchronous motor  3- Crank connecting rod  4-Walking beam
5-Horsehead  6- Sucker rod  7- Downhole oil production unit

2.1. Three kinds of balance scheme design
The ultimate goal of balance is to make the torque of the crank tend to be constant. The mechanical
balance of the pumping unit includes three balance methods: crank balance, beam balance, and
compound balance. During the analysis of the balance state of the pumping unit, the net torque of the
crank output shaft will show fluctuation characteristics. If the fluctuation characteristics are too large, it
will seriously affect the efficiency and use efficiency of the linkage mechanism and the direct drive
motor, and deteriorate the sucker rod string. The working conditions increase the risk of rupture of the
sucker rod string. Therefore, a reasonable selection of the balance method is of great significance for
solving the large torque of the crank output shaft of the direct-drive beam pumping unit. The following
The figure shows the schematic diagram of the structure of the pumping unit under three different balance modes:

**Figure 2. Schematic diagram of three balanced structures**

2.1.1. Analysis and calculation of force on walking beam-cross beam-connecting rod-crank. Taking the walking beam as the research object, the connecting rod force can be obtained by taking the suspended point load, the walking beam load, the connecting rod force, and the equivalent load force of the crank against the rotation center of the walking beam.

**Figure 3. Force diagram**

\[
P_\alpha = \left( P - \frac{A}{C} - Q_3 \frac{K_c}{C} \cos \varphi + \frac{Q_3}{g} \frac{K_c^2}{C} \frac{\alpha_c}{A} \right) \frac{1}{\sin \beta_1}
\]

Rod force component in the tangential direction of the crank:

\[
T = -\left( P \frac{A}{C} - Q_3 \frac{K_c}{C} \cos \varphi + \frac{Q_3}{g} \frac{K_c^2}{C} \frac{\alpha_c}{A} \right) \frac{\sin \alpha_c}{\sin \beta_1}
\]

2.2. Take the crank as the research object

In order to facilitate the analysis, the crank balance weight \( Q_5 \) and the crank's own weight \( q \) are converted to the crank pin. After the conversion, the torque to the crank rotation center remains unchanged, and the converted equivalent load is represented by \( Q_z \).
Figure 4. Schematic diagram of crankshaft force analysis

The torque produced by the crankshaft output torque M, the weight of the crank balance weight and the equivalent load of the crank's own weight together overcome the torque produced by the tangential force T.

Obtained by the crank crankshaft output torque equilibrium condition M:

$$\theta = -\alpha - \beta$$

$$(3)$$

By simplifying the above formula (3), the torque at the crankshaft of the beam pumping unit in three different balance modes can be obtained:

1) The torque at the compound balance crank is:

$$M = TF \left[ (P - B) - \frac{K_c}{A} Q_{gb} \right] - M_{max} \sin \theta$$

$$(4)$$

2) The torque at the crank balance crank is:

$$M = TF \left[ (P - B) \right] - M_{max} \sin \theta$$

$$(5)$$

3) The torque at the balance crank of the walking beam is:

$$M = TF \left[ (P - B) \right] - \frac{K_c}{A} Q_{gb}$$

$$(6)$$

To sum up: Through the analysis and calculation of the forces on the beam and crank, it is obvious that the torque on the crank output shaft of the beam pumping unit is the smallest under the compound balance mode. Therefore, the compound balance is selected as the balance method of the direct-drive beam pumping unit. It effectively solves the problem of large torque on the crank output shaft caused by the hanging point load and balance weight of the traditional beam pumping unit.

3. Analysis based on Adams simulation solution
Adams is a modeling, solving, visualization technology in one of the virtual prototyping software. In the early stage, the professional 3D modeling software Solidworks was used to establish the solid 3D model, and the parts were assembled in the assembly drawing environment. Then save the assembled model in (X_T) format and import it into Adams software, Add key tasks such as creating constraint pairs, rotating pairs, driving forces, and applying loads, as shown in Figure 5 below.

References are cited in the text just by square brackets [1]. Two or more references at a time may be put in one set of brackets [3, 4]. The references are to be numbered in the order in which they are cited.
in the text and are to be listed at the end of the contribution under heading references, see our example below.

Figure 5. Three-dimensional virtual prototype model of pumping unit.

Add in ADAMS virtual prototype direct drive pumping driving relationship with the constraint as follows: establish a fixed constraint between the base and the ground, to establish a fixed constraint between the beam and the horse head, beam - cross - connecting rod and crank, Cranks and permanent magnet synchronous motor shafts establish a rotation pair constraint, and add a rotary drive at the hinge joint between the crank and the motor shaft

Table 1. Direct drive pumping unit virtual prototype constraint list

| Two connecting members                  | Constraints   |
|----------------------------------------|---------------|
| Base-Earth                             | Fixed joint   |
| Walking Beam - Horsehead               | Fixed joint   |
| Walking Beam - Equalizer               | Revolute Joint|
| Equalizer - Pitman                     | Revolute Joint|
| Pitman -Crank                          | Revolute Joint|
| Crank - Permanent magnet synchronous motor shaft | Revolute Joint|

The stroke rate of the pumping unit is 12r/min, and the kinematics simulation of the direct-drive beam pumping unit is performed. The simulation time is set to 60s and the number of steps is 6000 steps. The following figure shows the suspension point displacement, suspension point speed, and suspension point acceleration curve of the direct-drive beam pumping unit.

Figure 6. Displacement, velocity and acceleration curve of the suspension point of the pumping unit
It can be seen from the figure that the displacement curve of the suspension point is sinusoidal simple harmonic motion, and the maximum displacement value is 1.8m. Secondly, it can be concluded in the figure that when the donkey's head suspension point is at the top and bottom dead points, the suspension point is displaced, the suspension point has the largest acceleration, and the suspension point velocity is close to zero. The kinematics simulation of the pumping unit was carried out in ADAMS, and the movement law of the suspension point was accurately obtained.

Dynamic simulation test: The dynamic analysis of the pumping unit is to study the dynamic response of the whole four-bar mechanism under the action of the load force of the suspension point.

\[ \text{Figure 7. Optimization front crank torque graph} \]

\[ \text{Figure 8. Optimized torque diagram} \]

4. Conclusion

By comparing and analyzing the changes in the crankshaft torque of the direct drive beam pumping unit before and after the improvement, it is found that the improved crankshaft torque value has been reduced, and the average value of the torque in a cycle is also reduced, which effectively improves the pumping problem of jitter when the machine is started indicates that the improved crank device has significantly improved the problem of large torque on the motor shaft of the direct-drive beam pumping unit, effectively reducing the output power of the motor, and realizing energy saving and consumption reduction.

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