Design and output characteristic analysis for power head of truck-mounted drilling rig

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Abstract. Truck-mounted drilling rig is an important equipment for coalbed methane drilling construction, and the power head is one of the main actuators for truck-mounted drilling rig which has significant influence on technical feature of drilling rig. Now the power head of the rig is mostly driven by the motor + gear reduction unit to drive the main axle, the load change with the time, which had more influence on the rotation circuit. At the basis of analysis on load characteristics, a hydraulic control system with two-pump and two-circuit control was designed. The dynamic analysis model of the system is established, and the output characteristics of the system under no-load starting and on load starting are analysed. The analysis results show that: the response time of no-load starting pressure is 0.3s, the response time of on load starting pressure is 0.9s, the greater the load, the longer the response time; the output speed of the system reaches 120 r/min in the stable state.

1. Introduction
The truck-mounted drilling rig has the advantages of mobility, flexibility and high efficiency [1-3], which is the best tool for coalbed methane exploration and development drilling construction. The power head is the core part of the drilling machine [4], and its main function is to transmit the torque and rotation speed required for rotary drilling to the drilling tool and drive the drilling tool to rotate. In addition, it can cooperate with other devices to complete the screwing and unloading of drill pipe.

However, the research and development of domestic full hydraulic vehicle mounted drilling rig is still in its infancy [5]. The design of important systems of truck-mounted drilling rig, such as rotary loop (also known as power head drive loop), mainly focuses on the maximum torque and rotary speed, and lacks performance analysis and targeted design of rotary load. It is necessary to make an in-depth analysis and Research on the load characteristics, system design and output characteristics of the rotary circuit.
2. Structural characteristics and load characteristics of power head

2.1. Structural characteristics

At present, the power head of truck-mounted drilling rig is mostly realized by motor + reduction gear set, and its transmission principle is shown in Figure 1. According to the demand of output torque and rotation speed, reasonably select the motorflow, motor quantity and gear transmission ratio.

![Figure 1. Schematic diagram of power head transmission](image)

2.2. Load characteristics

In normal drilling and hole sweeping operations, the load torque of power head is a certain value under ideal conditions (line 1 in Figure 2). Under the actual working condition, the resistance encountered by the drilling tool in the hole (friction between the drill pipe and the hole wall, resistance consumed by the bit breaking the rock) is constantly changing. In addition, the drilling system is a slender rod system with typical elastomer characteristics. When the resistance to rotation disappears suddenly, the drilling system will drive the power head to rotate, that is to say, the output of power head is negative. It can be seen that the load of power head has the characteristics of pulsation and randomness, and even negative value may appear (line 2 in Figure 2). This kind of load has the effect on the fluid the damage of the pressure motor is sometimes fatal, which will also cause the swing system to run out. Therefore, it is very useful to design the system according to the load characteristics and improve the stress conditions of the motor and the working stability of the swing system through system optimization.

3. Design of rotary system [6-8]

According to the load characteristics, the hydraulic system is developed, and the system principle is shown in Figure 3.

![Figure 3. Hydraulic schematic diagram of rotary system](image)
The motor of the rotary circuit is driven by two circuits in parallel. The main pump a11v130 drives the motor to rotate through the M7 valve to realize fast rotation, which is used for working conditions such as hole sweeping and normal drilling; the auxiliary pump drives the motor through the M4 valve to realize slow rotation, which is used for working conditions such as drilling rod screwing out. The oil outlet of the main pump and the auxiliary pump are respectively connected to the inlet of the shuttle valve, and the outlet of the shuttle valve provides the oil source for the pilot valve through the pressure reducing valve. The pilot valve controls the main valve and the reversing valve respectively. Variable pump is adopted for main pump and auxiliary pump, which can realize stepless adjustment of rotation speed; hydraulic control double speed motor is adopted for motor, which operates manual reversing valve, cuts off or connects high-pressure oil and motor flow control mechanism, and the motor will switch between the maximum flow and the minimum flow, which increases the speed regulating range of power head and has stronger process adaptability.

4. System modeling and parameter calculation

4.1. System modeling
According to the front hydraulic system and component selection, build the simulation analysis model of the rotary circuit. The slewing circuit includes fast slewing circuit and slow slewing circuit. Four a11v130 pumps in the fast slewing circuit drive four Eaton 10000 series dual speed motors through M7 valve. The main technical parameters are shown in Table 1:

| Name              | parameter | parameter |
|-------------------|-----------|-----------|
| Rated torque      | /N.m      | 30000     |
| Rated speed       | /r/min    | 120       |
| Rated pressure    | /MPa      | 23        |
| Rated Flow        | /L/min    | 600       |
| Transmission ratio|           | 3.77      |

Since the maximum speed of the fast rotation of the vehicle mounted drilling rig reaches 120 r/min, the moment of inertia of the power head of the drilling rig is large in the process of rotation. In order to reduce the impact of the motor at the high speed of the power head, a buffer oil replenishing circuit is designed in the power head rotation circuit. The fine model of quick rotation of the power head is established as shown in Figure 4, and the parameter design is shown in Table 2.

Figure 4. The model of quick rotation of the power head
Table 2. Parameters of rotary system

| Name              | Parameter          | Number | Number |
|-------------------|--------------------|--------|--------|
| Motor flow        | /ml/r              | 130    | 4      |
| M7 valve flow     | /L/min             | 600    | 1      |
| M7 valve pressure | /MPa               | 24     |        |
| Motorflow         | /ml/r              | 665/332| 4      |

4.2. Moment of inertia

The moment of inertia is an important technical parameter to study the dynamic characteristics of the hydraulic system of the rotary system. The power head and the drill stem are connected by threads. The main shaft and the drill stem of the power head rotate in the same axis. Relatively speaking, the weight of the drill bit is small and the calculated rotary inertia is ignored. The rotary inertia of the rotary system is:

\[ J_z = J_d + J_g \] (1)

Where \( J_d \) is the moment of inertia of the rotating parts of the power head for the turning center, \( J_g \) is the rotary inertia of the drill pipe to the rotary center.

(1) calculation of moment of inertia of power head

The power head is composed of motor, support plate, oil cylinder, rotary box, brake and main axle(Figure 5), the rotating parts include bearing inner ring, big gear, main axle, floating joint, water closet inner axle etc. the structure is relatively complex, and the method of calculating the moment of inertia of a single part is complicated, which can be calculated by three-dimensional software.

1-motor; 2-bracket; 3-oil cylinder; 4-rotation box; 5-brake; 6-main axle

**Figure 5.** 3D model of power head

**Figure 6.** Simplified model of drill pipe string

Firstly, in the UG drawing software, the WCS of the power head assembly is overlapped with the absolute coordinate system, the coordinate origin is located on the center line of the spindle, and the Z axis of the coordinate system is overlapped with the rotation center. Set the corresponding density attribute for the rotating parts, and calculate the corresponding weight and center of gravity coordinates. The "measuring body" function in UG analysis module is used to calculate the detailed quality attributes of the assembly body. The calculation results show that:

\[ J_d = I_{zc} = 9.11 \text{ kg/m}^2 \] (2)
4.3. rotary inertia of drill string
The supporting drill pipe of the vehicle mounted drilling rig is a slender rod body with the end thickened. Because the length of the end thickened part is short and the weight changes little, the drill pipe string can be simplified as a cylindrical homogeneous slender rod, and the weight of the drill pipe string increases with the length. As shown in the figure, the inner diameter of the drill pipe is $r$, the outer diameter is $R$, and the rotation center axis is $Z$.

Take a micro section on the cylinder, and the surface density of the ring is:

$$\sigma = \frac{dm}{\pi(R^2-r^2)} \quad (3)$$

Area: $dS = 2\pi r dr$;
Quality: $dm = \sigma dS = 2\pi r dr$;

The moment of inertia of cylinder to $Z$ axis is:

$$dJ = \int_r^R (2\pi \sigma r dr) r^2 = \int_r^R 2\pi \sigma r^3 dr = \frac{1}{2} \pi \sigma (R^4-r^4) = \frac{(R^2+r^2)^2}{2} dm \quad (4)$$

The moment of inertia of the whole cylinder is:

$$J_0 = \int dJ = \int_0^m \frac{R^2+r^2}{2} dm = \frac{m}{2} (R^2 + r^2) \quad (5)$$

The quality of drill string is:

$$m = \pi (R^2 - r^2) \cdot L \cdot \rho \quad (6)$$

The rotary inertia of drill string is:

$$J_g = \frac{\pi}{2} L \rho (R^4 - r^4)$$

The common specification of drill pipe for vehicle mounted drilling rig is G105 steel grade petroleum standard, the outer diameter of drill pipe is 127 mm, the inner diameter is 108 mm, then, $J_g = 1.53L$. The moment of inertia of the rotation system is:

$$J_z = J_d + J_g = 9.11 + 1.53L \quad (7)$$

5. Output characteristic analysis

5.1. Start characteristic under no-load
In order to simulate the dynamic characteristics of the no-load starting system of the power head, obtain the pressure and flow step fluctuation characteristics of M7 valve and motor in the rotating circuit from the starting to the steady-state process, as well as the dynamic response time. At 0s of the time axis of the analysis model, add the M7 valve rotary linkage forward conversion signal, and the analysis results are shown in Figure 7 to Figure 10.

The moment of inertia of the rotary system is the moment of inertia of the power head, $J_z = 9.11 kg.m^2$, the opening pressure of the buffer valve is set to 23MPa, and the friction load is set to 1000 Nm.

**Figure 7.** Flow characteristic curve of rotary slice in M7 valve
Figure 8 shows the flow characteristic curve of M7 valve rotary unit. It can be seen that when the working flow of M7 valve rotary unit rises from 0 to a stable value of 0.3s, and when the power head changes from static to rotating, the system flow fluctuates obviously. As can be seen in Figure 8, during the no-load start up of power head, the system pressure response speed is fast, the working pressure of M7 valve reaches 22.5MPa at the moment of response, and the pressure enters into a stable state after 0.3s. During the rotating process of the power head, the pressure difference between the front and back of the multi-channel valve is basically unchanged, and the pressure difference is about 2MPa.

As can be seen in Figure 9, the speed of the power head reaches the maximum value through 0.35 from zero. When the valve port is fully open, the rotating speed of the power head is 120 R / min, and the rotating speed is stable during no-load rotation.

As can be seen in Figure 10, the load and flow characteristics of a single motor are basically the same as those of the multi-channel valve, and the fluctuation frequency is the same, indicating that the system responds quickly to the operation command of fast rotation (0.5s), and the fluctuation follow-up of the motor and valve is relatively consistent.

5.2. Start characteristic under load
At present, the hole depth of the vertical section in the mainstream coalbed methane production area in China is mostly within 500m. When calculating the dynamic characteristics of the start and stop of the rotary belt load, it is more reasonable to calculate 500m drill pipe. The rotary inertia of the rotary system $J_L = (9.11 + 1.53 \times 500)$ kg can be obtained by bringing $L = 500m$ into formula 7.

In order to simulate the dynamic characteristics of the on load starting system of the power head, obtain the pressure and flow step fluctuation characteristics of M7 valve and motor in the rotating circuit from the starting to the steady state process, as well as the dynamic response time. At 2s of the time axis
of the analysis model, add the M7 valve rotary linkage forward conversion signal, part of the analysis results are shown in Figure 11 to figure 12.

Figure 11. Output revolving speed curve of power head

Figure 12. Flow and load characteristics curve of rotary motor

According to the data in Figure 11, the response time from the control signal to the stable motor speed is 0.9s after 500 m drill pipe load, which is increased compared with no-load start up. The fluctuation amplitude and time of motor load and flow also increase obviously. It shows that the larger the load is, the longer the response time is, and the number of system oscillations and overloads will increase.

It can be seen from Figure 12 that at the moment when the power head starts rotating, the maximum impact pressure of the rotating motor is 21MPa. During the starting process, the motor speed fluctuates obviously. After 4S, the motor speed tends to be stable.

6. Conclusion
The truck-mounted drilling rig is an important equipment for coalbed methane drilling construction, and the power head is the core component of the drilling machine. Based on the analysis of the load characteristics, the design of the hydraulic drive system of the power head is completed, the dynamic analysis model of the system is established, and the output characteristics of the system are analyzed under the conditions of no-load starting and on load starting. The analysis results show that: the response time of no-load starting pressure is 0.3s, the response time of on load starting pressure is 0.9s, the larger the load, the longer the starting response time; the system is in a stable state The output speed reaches 120r / min and reaches the design target.

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