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Research on the dynamic characteristics of mast mechanism of rotary drilling rig

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Abstract

In order to express the inherent complex dynamic characteristics of mast mechanism of rotary drilling rig synthetically and improve the smooth-going property of key parts and related hydraulic system in the lifting process. firstly, a dynamic model of mast mechanism based on Newton-Euler method is established, then a hydraulic system model of mast mechanism based on power bond graph is built up, a set of optimal installation position parameters are got for designers to refer by analyzing and comparing the impact of the dynamic characteristics in lifting process by changing the installation position of mast mechanism. The integrated modeling method is expected to be a theoretical basis for designing the mast system of rotary drilling rig.

Keywords: rotary drilling rig; mast mechanism; the dynamic characteristic; power bond graph

1. Introduction

Rotary drilling rig is construction machinery which is suitable for building into a hole in the building foundation engineering; it is widely used in the pile, diaphragm wall, foundation reinforcement and other infrastructure construction projects. The mast mechanism is a very important component in the work device of rotary drilling rig, the dynamic performance of mast mechanism has great impact on the main

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performance indexes of rotary drilling rig, such as the maximum output torque of power head, the hinge point force and the mast cylinder stress.

Till now the researches on mast mechanism of rotary drilling rig have mainly focused on the strength of components [1, 2] and on the mechanical behaviour of mast link frame system [3-6] and on the stability of rotary drilling rig [7], but there are hardly studies on the integrated modelling and simulating for mast mechanism of rotary drilling rig.

The research object is a certain type of rotary drilling rig in this study, in accordance with the dynamics relationship and stress analysis of mast mechanism in lifting process, we put forward the integrated modelling method to analyze the impact on the dynamic characteristics of mast mechanism in the lifting process by changing the installation position of mast mechanism, namely use Newton-Euler method to establish the dynamic mathematical model of mast mechanism; and set up power bond graph which can reflect the dynamic characteristics of the hydraulic system; then we can express the influence degree of the hinge point force and the cylinder piston rod stress quantitatively and get a set of optimal installation position parameters, the dynamic performance of mast mechanism is improved apparently.

Nomenclature

R_2 The fluid resistance of relief valve
R_4 The liquid resistance of hydraulic oil tube
R_8, R_{10} The fluid resistance of electromagnetic valve
R_f The sticky friction coefficient of cylinder
C_6 The liquid capacitance of hydraulic oil tube
C_{10} The comprehensive liquid capacitance from electromagnetic valve to hydraulic cylinder without rod cavity
C_{18} The comprehensive liquid capacitance from hydraulic cylinder with rod cavity to electromagnetic valve
A_1 The area of hydraulic cylinder without rod cavity
A_2 The area of hydraulic cylinder rod cavity
I_{15} The quality of hydraulic cylinder piston rod
S_f Pump theoretical flow
S_e External load of hydraulic cylinder
S_b Return oil pressure

2. Modeling mast mechanism dynamic of rotary

The mast mechanism of rotary drilling rig is composed of triangular connecting frame, hydraulic cylinder of mast and mast as shown in Fig.1. In the lifting process, lift-arm, connecting-rod, tripod and hydraulic cylinder of lift-arm don't move, mast rotates around hinge point F under the action of hydraulic cylinder of mast, the mast intermediate state I is regarded as the analysis object in the lifting process.

The motion analyzing diagram of mast mechanism is presented graphically in Fig.2, the connecting line between pin point F and G is regarded as the x axis, a Cartesian coordinate system is set up, Angle β is the angle between horizontal line and the x axis, the vector equation can be described as follows:

$$\begin{cases} r_1 + r_3\cos\alpha_3 = r_2\cos\alpha_2 \\ r_3\sin\alpha_3 = r_2\sin\alpha_2 \end{cases} \tag{1}$$

Derivative equation can be described by means of the vector equation (1) as follows:

$$\begin{cases} -r_2 \cos\alpha_2\omega_2^2 - r_2 \sin\alpha_2\varepsilon_2 = \\ \ddot{r}_3 \cos\alpha_3 - 2\dot{r}_3\omega_3 \sin\alpha_3 - r_3\cos\alpha_3\omega_3^2 - r_3\sin\alpha_3\varepsilon_3 \\ -r_2\sin\alpha_2\omega_2^2 + r_2\cos\alpha_2\varepsilon_2 = \\ \ddot{r}_3\sin\alpha_3 + 2\dot{r}_3\omega_3\cos\alpha_3 - r_3\sin\alpha_3\omega_3^2 + r_3\cos\alpha_3\varepsilon_3 \end{cases} \quad (2)$$

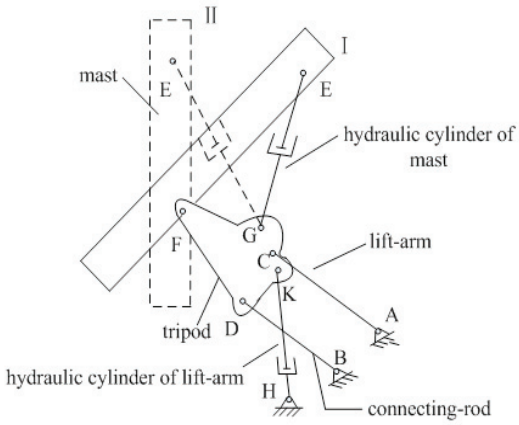

Fig. 1. Support system of rotary drilling rig

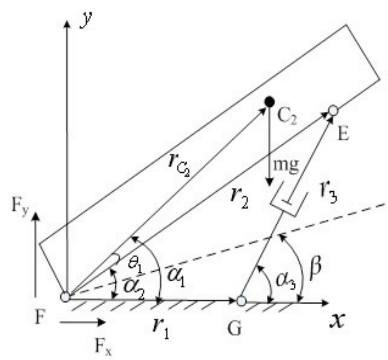

Fig. 2. Motion analyzing diagram of mast mechanism

According to (1) and (2), the velocity and acceleration equations of hydraulic cylinder of mast can be described as follows:

$$\dot{r}_3 = \frac{r_1 r_2 \omega_2 \sin\alpha_2}{r_3} \quad (3)$$

$$\varepsilon_2 = \frac{\ddot{r}_3\cos(\alpha_3-\alpha_2) + r_2\omega_2^2 - 2\omega_3\dot{r}_3\sin(\alpha_3-\alpha_2) - r_3\omega_3^2\cos(\alpha_3-\alpha_2)}{r_3\sin(\alpha_3-\alpha_2)} \quad (4)$$

Where ω_2 and ε_2 represent the angular velocity and angular acceleration of mast respectively, ω_3 and ε_3 represent the angular velocity and angular acceleration hydraulic cylinder of mast respectively, $\dot{r}_3$ and $\ddot{r}_3$ represent the piston rod velocity and acceleration of hydraulic cylinder of mast respectively.

Rigid body FE rotates on the fixed axis which through point F. Its kinematic differential equations are expressed as follows:

$$\begin{cases} F_x - F_N\cos(\alpha_2+\theta) + mg\sin\beta = 0 \\ F_y + F_N\sin(\alpha_2+\theta) - mg\cos\beta = 0 \\ F_N r_2\sin\theta - mgr_{c_2}\cos(\alpha_2+\theta_1-\beta) = J\varepsilon_2 \end{cases} \quad (5)$$

Where J is the moment of inertia that rigid body FE rotates on the fixed axis through point F, r_{c_2} is the distance between the center of mass point C_2 and the rotary center point F.

3. Modeling hydraulic control system of mast mechanism of rotary drilling rig

3.1. The model of hydraulic control system of mast mechanism based on power bond graph [8-10]

The hydraulic system graph of mast mechanism of rotary drilling rig is shown in Fig.3, in the lifting process, the hydraulic cylinder of lift-arm doesn't work, solenoid valve controls the movement of the mast cylinder.

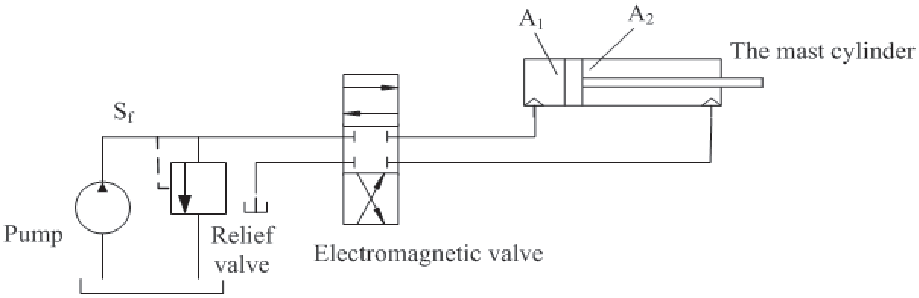

Fig. 3. Hydraulic system of mast mechanism of rotary drilling rig

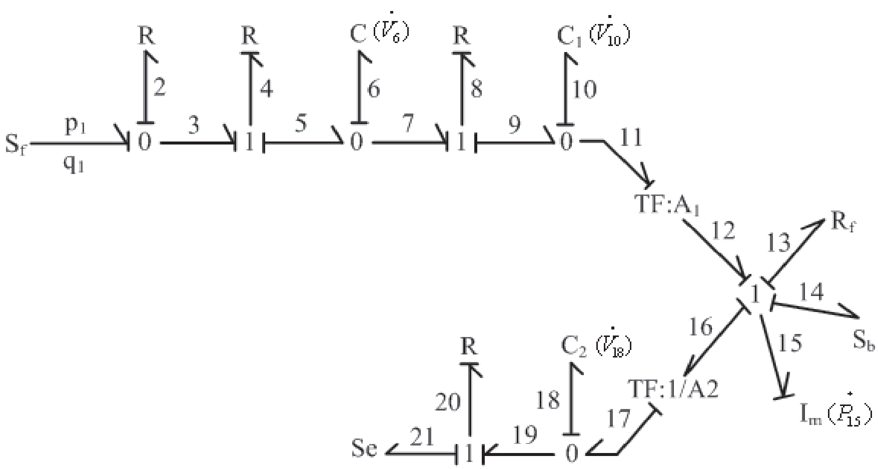

Fig. 4. Hydraulic system power bond graph of mast mechanism of rotary drilling rig

According to the dynamic relationship between the mast and the mast cylinder, in order to analyze the impact of mast cylinder and hinge point caused by the installation position of mast cylinder, we need to require angular acceleration - time curve in the lifting process and then establish the model of hydraulic control system of mast mechanism based on power bond graph as shown in Fig.4.

To simplify the mathematical model of the hydraulic system, the pump is considered as a constant current source in the modelling process. According to the actual situation, we ignore pump leak, pipeline distribution effect and cylinder leak. Fluid capacitance and fluid resistance are considered because of the length of the hydraulic oil hoses, but we should take into account fluid resistance and ignore fluid capacitance in the return oil process.

According to the relationship of each power bond in Fig.4, we can get the state equation (6).

$$\begin{cases} \dot{V}_6 = \dfrac{R_2}{R_2 + R_4} S_f - \dfrac{R_4 + R_8}{R_8 (R_2 + R_4)} \dfrac{V_6}{C_6} + \dfrac{R_4}{R_8 (R_2 + R_4)} \dfrac{V_{10}}{C_{10}} \\ \dot{V}_{10} = \dfrac{1}{R_8} \left(\dfrac{V_6}{C_6} - \dfrac{V_{10}}{C_{10}}\right) - \dfrac{P_{15}}{I_{15}} A_1 \\ \dot{P}_{15} = \dfrac{V_{10}}{C_{10}} A_1 - \dfrac{P_{15}}{I_{15}} R_f - \dfrac{V_{18}}{C_{18}} A_2 - S_e \\ \dot{V}_{18} = \dfrac{P_{15}}{I_{15}} A_2 - \dfrac{V_{18}}{C_{18}} \dfrac{1}{R_{20}} \end{cases} \qquad (6)$$

3.2. Hydraulic system block diagram model of mast mechanism

The system diagram is described based on the bond graph and the effort - flow variable calculation equation as shown in Fig.5.We ignore the effect of constant flow pump in the bond graph model, ω_m represents the constant speed of engine, S_f is the constant flow of control valve, the output signal is mast angle acceleration ε_2 .

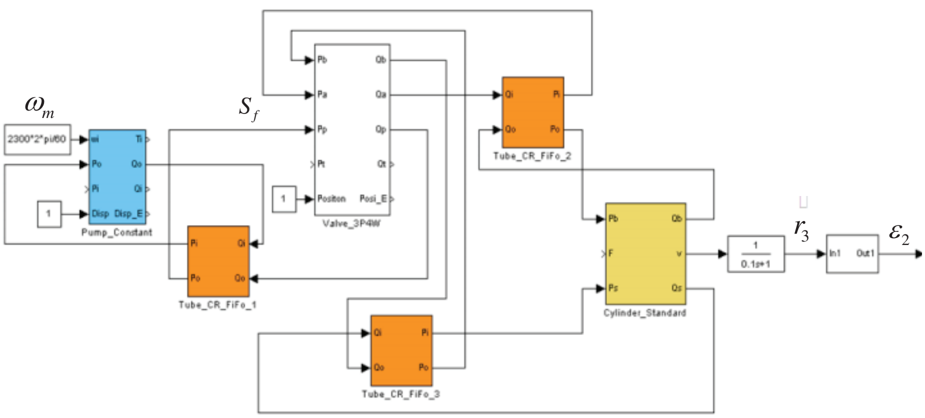

Fig. 5. Hydraulic system block diagram of mast mechanism of rotary drilling rig

3.3. Overview model of dynamics and hydraulic system of mast mechanism

According to the mast mechanism dynamic equation as shown in above equation (6) which is deduced by Newton-Euler method, a dynamics simulation model is built in Simulink platform, we can express the dynamic characteristics of mast mechanism synthetically combined with the hydraulic control system block diagram of mast mechanism.

4. Calculation example analysis

4.1. Calculation example

Taking a certain type of rotary drilling rig as the research object, the main mechanical parameters are shown in Table.1. The mast hydraulic cylinder of rotary drilling rig plays a very important role in the mast lifting process, therefore we should design the installation position of hydraulic cylinder r_2 reasonably, namely the distance between the hinge point E and hinge point F, in order to improve the performance of mast mechanism.

According to the structure characteristics of calculation object (namely the mast cylinder of rotary drilling rig), different installation position r_2 was chosen successively, such as r_2=3.7m, 3.9m, 4.1m, 4.2m, 4.3m, 4.5m, 4.7m, the calculation was operated under the Matlab/Simulink environment, and the simulation time is 45 seconds.

Fig.6 indicates the entire force process of the piston rod of mast cylinder, Fig.7 indicates the constraint force changing process of hinge point F, Fig.8 and Fig.9 reflect the pressure changing process of the mast cylinder without rod cavity and with rod cavity. We can see that Fig.6-9 reflect the impact on the dynamic characteristics of mast mechanism by changing the installation position of mast cylinder comprehensively.

Table.1 Main parameters of mast mechanism of certain type rotary drilling rig

parameter name	symbol/unit	value
The distance between hinge point F&G	r_1/mm	1431
Centroid vector of mast	r_{c2}/mm	3735
The inertia of mast	$J/kg\cdot m^2$	1.1×10^{10}
The quality of mast	m/kg	2.64×10^4
The cylinder diameter of mast	D/mm	180
The piston rod diameter of mast	d/mm	125
The trip of mast cylinder	L/mm	2080
The shortest length of mast cylinder	$L_{\min}/mm$	2970
The angle between C_2F and EF	θ_1/rad	0.2355
The angle between EF and FG	α_2/rad	0.5～2.01
The angle between tripod and the horizontal plane	β/rad	0.33

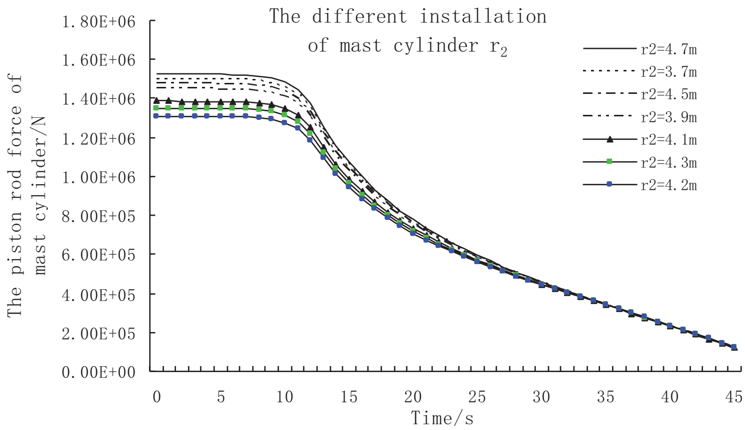

Fig. 6. The force process of the mast cylinder piston rod in different installation position

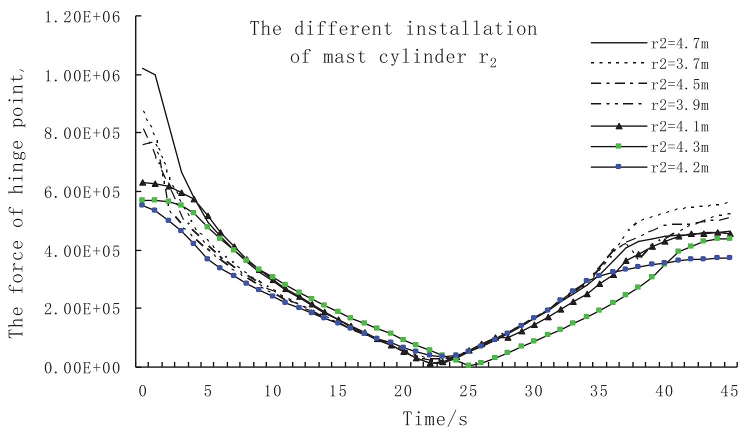

Fig. 7. The constraint forces changing process of hinge point F in different installation position

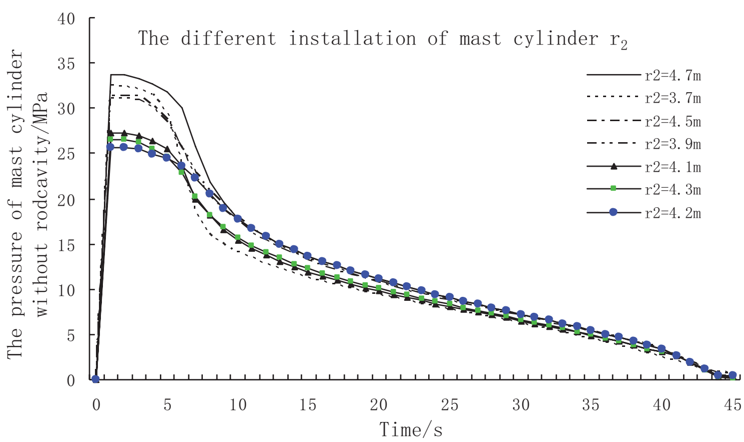

Fig. 8. The pressure of the mast cylinder without rod cavity in different installation position

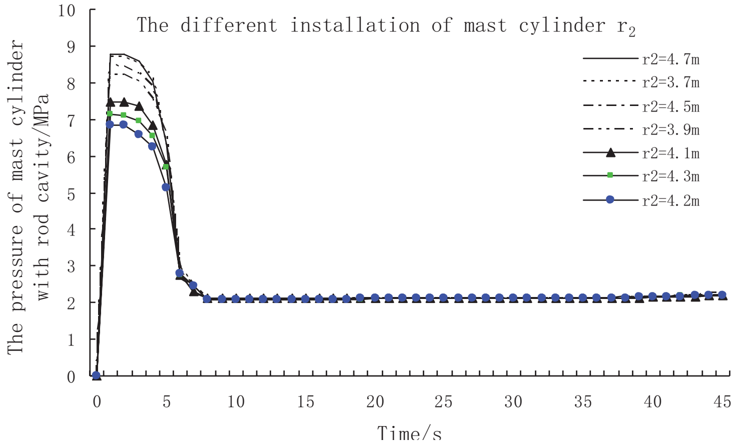

Fig. 9. The pressure of the mast cylinder with rod cavity in different installation position

4.2. Results analysis and discussion

Through the analysis of the simulation results, it can be concluded that:

(1) In the mast whole lifting process (namely the angle between mast EF and tripod FG changes from 30° to 110°), the stress of the piston rod becomes the smallest when hydraulic cylinder installation position changes from 4.1 m to 4.3 m. Compared to other installation position, the vertical load of mast cylinder piston rod is smaller, meanwhile, considering the generated influence of hydraulic impact of the three four-way electromagnetic valve when opening, we can also see the pressure changes smoothly at the time, the peak value fluctuations within±5%. As shown in Fig.6.

(2) Restraining forces of the hinge point F fluctuate smoothly when the beginning of mast lifting process, and the pressure shock is smaller. See Fig.7.

(3)When the mast hydraulic cylinder installation position r_2 changes from 4.1m to 4.3m, compared to other installation position, the pressure shock of the hydraulic cylinder without rod cavity and with rod cavity is smaller and less influence on the stress of the piston rod at the beginning of mast lifting process. The bending deformation problems of hydraulic cylinder caused by excessive pressure impact have been improved in a certain extent. As shown in Fig.8 and Fig.9.

In conclusion, mast hydraulic cylinder installation position has great influence on the force of hydraulic cylinder piston rod and restraining forces of hinge points. When the installation position r_2 changes between 4.1 m and 4.3 m, compared to other installation position, the piston rod stress is smaller, which can reduce the pressure shock effectively, and avoid the longitudinal bending deformation risk of the hydraulic cylinder. It should be pointed out that, the integrated modelling method used in this paper can be also applied to other types of rotary drilling rig.

5. Conclusion

The simulation model of mast mechanism of rotary drilling rig was built by using the integrated modelling method, then we can express the influence on the reliability of mast system of rotary drilling rig quantitatively by changing the installation position of mast cylinder, the analysis results show that the reasonable installation position of mast cylinder is one of the key factors in the mast mechanism design. The integrated modelling method also provides certain theoretical guidance for other types of rotary drilling rig structure design.

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