Structural Optimum Design and Analysis of the Mast of Rotary Drilling Rig Based on Finite Element Method

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Abstract: The objective of this study is to minimize the mast deformation by structural optimization of the mast of rotary drilling rig in order to better control its functional operation and improve its performance. For this purpose, a novel optimization scheme for the mast of rotary drilling rig is formulated using 3D graphics software Pro/E together with Finite Element Method. Back sliding wheel installed on the mast is firstly proved to reduce the deformation of the mast of rotary drilling rig effectively. The position of back sliding wheel relative to the mast of rotary drilling rig is adjusted, together with the position of pulley yoke, to obtain the minimum deformation of the mast of rotary drilling rig, which improves the stability of the mast of rotary drilling rig. Optimization efficiency and computational accuracy are demonstrated numerically.

Keywords: Back sliding wheel, FEA, mast, pulley yoke, rotary drilling rig

INTRODUCTION

In recent years, rotary drilling rig that fits out all kinds of drilling tools, with multi-function form, brings into play bigger function in capital construction engineering and suffers the widespread concern. As huge construction equipment used to implement pore-forming task in the construction foundation work, rotary drilling rig has already become a high and new technology product in the domain of piling machinery and is widely applied in high-rise building, railroad, highroad, bridge and city transportation construction and so on (Wijk, 1991; Robin and Charles, 2003; Abramov et al., 2009).

Field experience manifests that the mast deformation of rotary drilling rig is one of the major cause for a deteriorated drilling performance of rotary drilling rig. It is crucial to minimize the mast deformation by structural optimization to control its functional operation and improve its performance. The mast, as a support device of rotary drilling rig and an important element of rotary drilling rig, is used to sustain power head and drilling pipe of rotary drilling rig. If the excessive deformation of the mast of rotary drilling rig occurs, the positioning accuracy of drilling hole is largely affected, which results in hole-deviation and orientation inaccuracy. The problem of the mast deformation of rotary drilling rig has been recognized as one of the prime causes of deterioration in drilling performance of rotary drilling rig and was subjected to some early investigations as reported in reference (Wang, 2008; Kang et al., 2010). Continuous improvement of drilling performance poses a challenge to rotary drilling rig, therefore, how to reduce the mast deformation of rotary drilling rig has already become an important subject of structural optimum design of rotary drilling rig.

Recognized as one of the most powerful numerical tools for solving large-scale structural problems of complex geometry, the finite element method (FEM) attracted several investigators in this field (Liu et al., 2009; Khulief and Al-Naser, 2005; Batako et al., 2004; Christophe et al., 2009; Qin and Yao, 2007; Zhao et al., 2006). It is noted that the main features of most of the reported papers will be outlined with reference to the improvement of stiffness and strength of the mast of rotary drilling rig through advanced design and manufacture technique. These investigations focused on evaluating structural features, assembling and welding procedure of the mast of rotary drilling rig, especially mechanical properties of the mast of rotary drilling rig, however, the functional analysis of back sliding wheel on decreasing the deformation of the mast of rotary drilling rig has not been considered as yet. As a step in this direction, this study offers a new method to realize optimization analysis of the mast of rotary drilling rig due to position change of back sliding wheel and pulley yoke relative to the mast of rotary drilling rig.

In order to improve the stability of the mast of rotary drilling rig, this study presents a finite element model of the entire mast of rotary drilling rig including back sliding wheel and pulley yoke. 3D graphics software Pro/E is firstly used to establish solid model of the mast of rotary drilling rig and then the model is imported into the finite element analysis software for further optimization analysis.
element analysis software Ansys to calculate the working characteristics and to perform the deformation analysis of the mast of rotary drilling rig. It is concluded that the structure of the mast of rotary drilling rig with back sliding wheel is proved to be more effective than that without back sliding wheel to reduce the deformation of the mast of rotary drilling rig. On this basis, the position of back sliding wheel relative to the mast of rotary drilling rig is adjusted, at the same time, the position of pulley yoke relative to the mast of rotary drilling rig is also adjusted. The results indicate that these proposed methods are feasible to obtain the minimum deformation of the mast of rotary drilling rig, which will provide theoretical supports for optimization design and research of the mast of rotary drilling rig.

METHODOLOGY

Structural overview of the mast of rotary drilling rig: Multi-functional rotary drilling rig from Zoomlion, as research object, is applied to analyze deformation regularity of the mast of rotary drilling rig. Rotary drilling rig, in general, consists of many main subsystems: drilling tool, drilling pipe, power head, mast, pulley yoke, supporting mechanism, base plate and hydraulic control system. These subsystems are designed to work seamlessly together.

The mast of rotary drilling rig is regarded as slimline type member bar in the mechanics system. The mast discussed by the paper belongs to three-segment folding rod, includes upper mast, middle mast and lower mast, which mates with tripod mounted and parallelogram amplitude-change mechanism to together constitute working device of rotary drilling rig. Figure 1 shows a typical rotary drilling rig. The column of the mast puts to use concave-boxing type cross-section, makes use of 24 strengthening rib plates mounted inside the mast based on load distribution to enhance the entire mast’s intensity. Rotary drilling rig applies three sets of sliding wheel to adjust the direction of motion of steel wire rope of the winch, thereinto, two sets of sliding wheel are installed on pulley yoke, including main sliding wheel and auxiliary sliding wheel, meanwhile, a set of back sliding wheel is installed on the middle mast. Pulley yoke is located on top of the mast and the winch is located on the slewing platform. Hydraulic cylinder is installed on the middle mast. The height of the mast is 19.5 m.

Working principle of rotary drilling rig: The rotary drilling method, started by a French civil engineer in 1863, is the most common method that performs a rotary grinding action. Rotary drilling rig’s purpose is to get a hole from a surface location to a subsurface target at a specified depth in a safe and controlled manner. All the
equipment that makes up a rotary drilling rig is designed and manufactured to this aim (Fakhry, 2009; Catalin and Falcone, 2008). When rotary drilling rig is in functional mode, the torque provided by power head is actualized on drilling pipe and drilling tool, to keep drilling head rotating and cutting the underground object, at the meantime, the pressure from hydraulic cylinder drives drilling pipe and drilling tool to drill downward deeply. the residue will be forced to come into drilling tool and then the main winch hoists drilling pipe and drilling tool out of the ground, rotates a certain degree away from the orifice, opens the bottom door of drilling tool and then spills the residue and then closes the bottom door and then rotates back to the orifice and then goes on moving drilling pipe downward to place drilling head into the orifice.

Stress analysis of the mast of rotary drilling rig: When rotary drilling rig is under the working condition of drilling, the dynamic reducer is slewed to drive drilling pipe and drilling tool to be in drilling operation, resistance torque produced by digging the rock-soil is passed to the mast, the main load mode of the mast is torsion.

When rotary drilling rig is under the working condition of hoisting drilling tool, one end of steel wire rope is fixed on the reel of the winch, another end crosses through back sliding wheel of the middle mast, through auxiliary sliding wheel and main sliding wheel of pulley yoke and then is connected with the elevator of drilling pipe, as shown in Fig. 1. The perpendicular load component born by the mast mainly includes hoisting load and deadweight, thereinto, the hoisting load is composed of the weight of drilling pipe and drilling tool, the stickiness resistance of the soil and the resistance of vacuum negative pressure, the main load mode of the mast is eccentricity pressure.

The main aim of this paper is to discuss the mast deformation under the condition of eccentricity pressure, how to utilize back sliding wheel, adjust the position of back sliding wheel relative to the mast of rotary drilling rig and the position of auxiliary sliding wheel of pulley yoke relative to the mast of rotary drilling rig, in order to minimize the mast deformation and then realize structure optimization of the mast of rotary drilling rig. For the sake of the mast’s safety, the most hoisting load is defined as 25 ton, which completely satisfies design requirement of the mast of rotary drilling rig.

RESULTS AND DISCUSSION

FEA analysis of the mast of rotary drilling rig: Establish geometric model of the mast of rotary drilling rig: With an eye to complex structure and excessive assembled parts of the mast of rotary drilling rig, the powerful wildfire 4.0 Pro/E software is applied to three-dimensional entity model building of the mast of rotary drilling rig as shown in Fig. 2. Because the mast’s dead-weight also affects the mast deformation, the mass property of every component assembly of the mast must be input accurately, which includes material mass, center of mass and moment of inertia, so that the magnitude and location of gravity of the mast could be seized precisely when the load and constraint are exerted to the mast in the course of stress analysis.

Establish FEA model of the mast of rotary drilling rig: The attempt to use the FEM in this paper is dedicated to studying structural optimization and performance analysis of the mast of rotary drilling rig. Three-dimensional entity model from Pro/E software can be imported directly into FEA software, all kinds of property from entity model in the Pro/E can be inherited entirely, which includes initial position parameter and mass property of all component assembly of the mast. In order to be convenient for analytical calculations, when the mechanics effectiveness of FEA model can be guaranteed to accord with where it is to the greatest extent, simplification principles should be applied to modeling process (2008), as follows:

- Amplitude-change mechanism, base plate and the slewing platform connected with the mast should be regarded as rigid stationary body
- The load, constraint condition and supporting structure of the mast should conform with the requirements of mechanical equilibrium balance
- Except the gravity, the whole load should be translated into concentrated load
Fig. 3: Mechanical analysis of the mast of rotary drilling rig (a) working radius 4.53 m without back sliding wheel, (b) working radius 4.7 m with back sliding wheel, (c) working radius 5.58 m without back sliding wheel.

Fig. 4: Deformation of the mast of rotary drilling rig, (a) working radius 4.53 m without back sliding wheel, (b) working radius 4.7 m with back sliding wheel, (c) working radius 5.58 m without back sliding wheel.
Meanwhile, other basic assumptions must be put forward in the course of FEA modeling, which include:

- The whole mast is considered as homogeneous material
- The welding quality of the mast is qualified
- The influence of the bolt joint of the mast on integral stress of the mast is very weak and accordingly should be without consideration

In this case, the FEA modeling of the mast of rotary drilling rig can be established under three different working radius, as shown in Fig. 3.

**FEA result of the mast of rotary drilling rig**: In this study, the material parameters used in calculation are as follows: the material is Q345B, material density is 7.85 kg/m, elasticity module E = 206 GPa, Poisson’s ratio $\mu = 0.3$. The mast deformation of rotary drilling rig under three different working radius are shown in Fig. 4, it can be seen from the figure that the largest mast deformations of rotary drilling rig without back sliding wheel are 52.36 and 85.024 mm respectively, however, the largest mast deformation of rotary drilling rig with back sliding wheel reduces to 18.576 mm, thus it could be concluded that back sliding wheel can improve the mast deformation of rotary drilling rig greatly.

It can be seen from Fig. 1 that the main winch utilizes steel wire rope to support the hoisting load and deadweight during its working process, so pulley yoke will bear pressure or force from steel wire rope and then the load is transferred to the mast of rotary drilling rig. Because the direction of motion of steel wire rope is adjusted through three sets of sliding wheel, the magnitude and direction of the load exerted on the mast of rotary drilling rig is variable with the position of back sliding wheel relative to the mast of rotary drilling rig is adjusted, together with the position of pulley yoke relative to the mast of rotary drilling rig. That is, due to the fact that the location relation of drilling pipe and power head of rotary drilling rig, the position of main sliding wheel of pulley yoke relative to the mast of rotary drilling rig remains fixed or immovable, we can choose the position of back sliding wheel relative to the mast of rotary drilling rig and the position of auxiliary sliding wheel of pulley yoke relative to the mast of rotary drilling rig as two variables and simultaneously adjust them to control the mast deformation of rotary drilling rig.

Based on the above analysis, the distance between back sliding wheel and the mast of rotary drilling rig is firstly adjusted, which is represented by the symbol $L_1$, at

(a) $L_1 = 100 \text{ mm, } L_2 = 100 \text{ mm}$

(b) $L_1 = 200 \text{ mm, } L_2 = 100 \text{ mm}$
(c) \( L_1 = 300 \text{ mm}, L_2 = 0 \text{ mm} \)

(e) \( L_1 = 100 \text{ mm}; L_2 = 200 \text{ mm} \)

(d) \( L_1 = 400 \text{ mm}, L_2 = 100 \text{ mm} \)

(f) \( L_1 = 200 \text{ mm}, L_2 = 200 \text{ mm} \)
(g) $L_1 = 300$ mm, $L_2 = 200$ mm

(i) $L_1 = 300$ mm, $L_2 = 0$ mm

(h) $L_1 = 300$ mm, $L_2 = 300$ mm

(j) $L_1 = 350$ mm, $L_2 = 0$ mm
(k) \( L_1 = 400 \text{ mm}, L_2 = 0 \text{ mm} \)

Fig. 5: Deformation of the mast of rotary drilling rig

In this work, we present solutions for decreasing the mast deformation of rotary drilling rig using 3D graphics software Pro/E together with finite element method, unlike any previous research methods from early reported investigations. Two things result from this paper: first, to install back sliding wheel on the middle mast is confirmed to effectively improve the mast deformation of rotary drilling rig; secondly, the emphasis of this paper is not put on in-depth studies for mechanical properties of the mast of rotary drilling rig itself, but applies three sets of sliding wheel to adjust the direction of motion of steel wire rope of the winch and then to adjust the magnitude and direction of the load exerted on the mast of rotary drilling rig, in order to decrease the mast deformation of rotary drilling rig.

By the analysis and discussion of practical example, the conclusions tell us that it is feasible to introduce the general finite element software ANSYS to analyze the mast structure in the course of the whole structure design of rotary drilling rig. The result of FEA analysis shows that the minimum deformation of the mast of rotary drilling rig occurs under the condition of \( L_1 = 350 \text{ mm} \) and \( L_2 = 0 \text{ mm} \). The optimized project and its research achievement put forward by the paper provide theoretic supports for more optimization design and research of the mast of rotary drilling rig. At the same time, it’s therefore tremendously significant to intensify market competition of rotary drilling rig.

CONCLUSION

In this work, we present solutions for decreasing the mast deformation of rotary drilling rig using 3D graphics software Pro/E together with finite element method, unlike any previous research methods from early reported investigations. Two things result from this paper: first, to install back sliding wheel on the middle mast is confirmed to effectively improve the mast deformation of rotary drilling rig; secondly, the emphasis of this paper is not put on in-depth studies for mechanical properties of the mast of rotary drilling rig itself, but applies three sets of sliding wheel to adjust the direction of motion of steel wire rope of the winch and then to adjust the magnitude and direction of the load exerted on the mast of rotary drilling rig, in order to decrease the mast deformation of rotary drilling rig.

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