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Design and Simulation Optimization of Full Hydraulic Chuck

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Abstract: Rock fragmentation process by drilling rig is accomplished by the simultaneous effects of drill pipe rotation and axial downwards motions. Hydraulic chuck transfers engine power to drill pipe during the drilling and sampling process suchthatit's one of the most important components of drilling rig. Chuck available on the market, design is not considered clamping force and drilling capacity matching, resulting in slipped drill, injury drill or chuck destruction. This study designs a maximum clamping diameter 73 mm hydraulic chuck, focuses on the interaction mechanism of the gripper slips and drill pipe. A model to simulate and optimize the clamp mechanism and slips has been developed by the finite element analysis method, conclude the structure of the optimal size of the hydraulic chuck. This research may be a better suggestion on resolving the problems of pipe damage and slipping down. The study method would also be a reference for the design of other kinds of chucks. A model to simulate and optimize rainwater-harvesting systems for irrigation has been developed.

Key words: Hydraulic chuck, finite element analysis, optimization design, drilling rig

INTRODUCTION

Hydraulic chuck is one of the most key ancillary equipments of a coring drilling. Which has been used for clamping drill pipe, transmitting torque and axial thrust to the drill pipe. Driving the drill stem thrust and rotation, achieving plus/minus pressure drilling and providing the auxiliary movement under emergency situations (Boyadjieff and Merit, 1992).

It can also cooperate with gripper to unload and lift the drill pipe in hydraulic drive power head of drilling rig. The performance of the hydraulic affects the using reliability of a drilling rig greatly (Feng, 1993).

Nowadays, there are three types of hydraulic chuck used in drilling process, namely, spring type chuck, rubber chuck and full hydraulic chuck. Multi-parts and complicated structure of spring type chuck and rubber chuck leads troubles for maintenance and renewal of slips and other wearing parts. So, the study focus on the design of the type of full hydraulic chuck. Based on the working principle of full hydraulic chuck, the structural parameters of slips were analyzed concretely through the finite element approach in order to find a more reasonable design process.

MATERIALS AND METHODS

This full hydraulic chuck includes these parts, namely, main spindle, top cover, cylinder barrel, back plate, slips, slips bowl, pressed cover and piston. Figure 1 shows the integrated structure. Its working principle is: Firstly, hydraulic oil enters into the sealed cavity formed by the right top cover and cylinder barrel

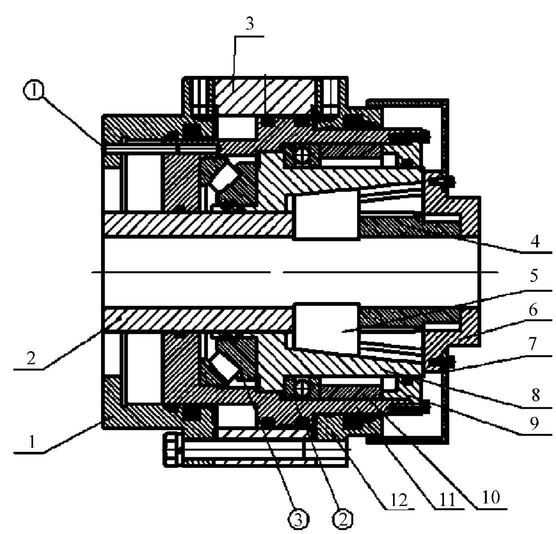

Fig. 1: Structure of full hydraulic chuck, 1: Left top cover, 2: Main spindle, 3: Cylinder barrel, 4: Back plate, 5: Slips, 6: Pressed cover, 7: Waterproof cover, 8: Slip bowl, 9: Top cover, 10: Rings for shoulder, 11: Piston, 12: Right top cover, ①: Clevis pins A, ②: Direction thrust ball bearings, ③: Thrust self aligning roller bearing

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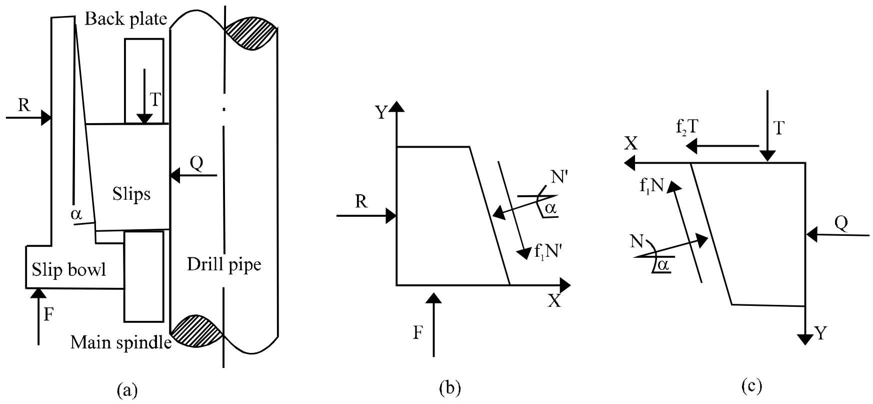


Fig. 2(a-c): (a) Load analysis of the full hydraulic chuck clamping the drill pipe, (b) Force analysis of the slip bowl, (c) Force analysis of the slips

through a small hole on the right top cover, the piston starts axial movement, at the same time, by the slope force amplifier, the slips moves relative to the main spindle and the slips moves in the radial direction, thereby the pipe is clamped. When the reversing valve is operated to let the sealed cavity open to the oil box, the pressure on the sealed cavity disappears. Hydraulic oil enters into the sealed cavity through a small hole on left top cover, the piston moves in opposite direction, thereby the pipe can be released. The chucking force could be adjusted by controlling the oil pressure in the sealed cavity, which is useful for the protection for drill pipes, especially thin wall drill pipes.

Maximum workload P_{max}: The bearing capacity of the hydraulic chuck is determined by the maximal workload among the following two conditions: Normal drilling and pull-out drilling (Feng, 1993).

Under normal drilling conditions, the load of the hydraulic chuck Pg is determined as follows:

$$P_g = \alpha \times \sqrt{P_y^2 + P_z^2} \tag{1}$$

where: P_z-axial thrust on the drill pipe[N]; P_y-circumferential force on the drill pipe[N]:

$$P_y = \frac{2Mn}{d} \tag{2}$$

where: Mn-torque on the drill pipe (N·m); d-drill pipe outside diameter (m).

Under pull-out drilling conditions, the load of the hydraulic chuck Pb is determined as follows:

$$P_b = \alpha \times P_{max} \tag{3}$$

where: α-safety factor , α = 1.25~1.6; P_{max}-the maximum pulling force produced by feeding mechanism [N].

By comparing P_g and P_b calculated from above Eq. 1 and 3, the larger one is taken to determine the maximum workload.

Equivalent clamping force Q: Equivalent clamping force Q is the necessary clamping force when the chuck is under the maximum workload:

$$Q = \frac{P_{max}}{f} \tag{4}$$

where: f-friction coefficient between slips and the drill pipe, the contact area between slips and drill pipe is smooth, noting that f = 0.10~0.15.

Solution of the axial thrust force of hydraulic cylinder: In order to determine the relationship between axial thrust of hydraulic cylinder and equivalent clamping force, the stress analysis was carried out when the drill pipe is clamped by the slips (Fig. 2a) (Wang *et al*., 2011). The stress analysis of the slip bowl and the slips are shown in Fig. 2b and c (Li *et al*., 2012; Zhu *et al*., 2010).

Where:

R	:	The acting force action on slip bowl[N]
N	:	The acting force between slip bowl and slips[N]
T	:	The acting force between slips and black plate[N]
Q'	:	The acting force between slips and the drill pipe[N]
F	:	The axial thrust force of hydraulic cylinder[N]
f_1, f_2	:	The coefficient of sliding friction, $f_1 = f_2$
α	:	Half-cone angle of the slips/slip bowl, α = 6~8°

N and N' are action-reaction forces, Q and Q' are action-reaction forces.

System of linear equations of the chuck will be completed according to statics conditions as follows: (1) The resultant force of horizontal direction is zero; (2) The resultant force of perpendicular direction is zero; (3) The friction force is proportional to the positive pressure. Thus, the equations are listed as follows:

For the slip bowl:

$$\Sigma X = R - N'\cos\alpha + f_1 N'\sin\alpha = 0 \tag{5}$$

$$\Sigma Y = F - f_1 N'\cos\alpha - N'\sin\alpha = 0 \tag{6}$$

For the slips:

$$\Sigma X = Q' + Tf_2 + f_1 N\sin\alpha - N\cos\alpha = 0 \tag{7}$$

$$\Sigma Y = T - f_1 N\cos\alpha - N\sin\alpha = 0 \tag{8}$$

Therefor, the solution of the axial thrust force of hydraulic cylinder is:

$$F = \frac{Q(f_1\cos\alpha + \sin\alpha)}{(1 - f_1^2)\cos\alpha - 2f_1\sin\alpha} \tag{9}$$

RESULTS

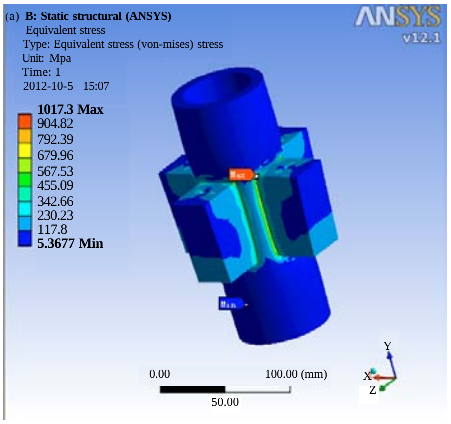
Finite element analysis research of the slips: In order to find the optimized structure of the slips, stress and strain for the slips under the maximum workload have been analyzed. The result would provide theoretical assistance for the practical design (Chen and Kikuchi, 2001; Neumann and Hahn, 1998).

The study use high yield strength material 20 CrMnTi and 42 CrMo for the slips and the drill pipe, respectively. According to the contact relationship between the slips and the drill pipe (Spur and Mette, 1998), 3D models were built in Solidworks for the finite element analysis firstly, which is the basis for the optimum design; next, virtual assembling of slips and the drill pipe is accomplished after dimensional optimum designing in ANSYS Workbench. Through meshing the assembly and calculating the example, the stress-strain diagrams were obtained and shown in Fig. 3a and b.

From the above stress diagram, the maximum stress in the assembly is the place where the slips contact with the drill pipe. The maximum stress is 1017.3 Mpa which is far beyond the yield limit of both the drill pipe and the slips, so the structure of the slips must to be optimized in design. The maximum strain of 0.08 mm is at the back of the slips, which is so small to be neglected.

Structural optimization of the slips of Full Hydraulic Chuck: In order to analyze the size of the slips influencing on the stress of itself, which structure shown in Fig. 4, the author choose the width L2, the height Extrudel.FD1, the sideline chamfering Fblendl.FD1 and the distance from arc center to base line of L5 as the design variables, take the maximum stress of the slips as objective function (Song, 2012). The static analysis was based on ANSYS Workbench. The maximum stress correspondence with a series of design variables is shown in Table 1.

Where:
Plane4.L2: The width of slips
Extrudel.FD1: The height of slips
Fblend1.FD1: The sideline chamfering of slips
Plane4.L5: The distance from arc center to base line



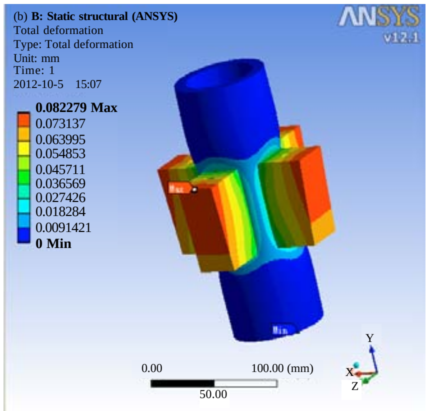


Fig. 3(a-b): (a) The coupling stress when full hydraulic chuck clamps a drill pipe, (b) The coupling strain when full hydraulic chuck clamps a drill pipe

Table 1: The maximum stress corresponding to a series of design variables

A	B	C	D	E	F
Name	P1-plane 4.L2 (mm)	P2-Extudel.FD 1 (mm)	P3-Fblend.FD1 (mm)	P5-plane.L5 (mm)	P4- Equivalent stress maximum (Mpa)
1	32	68	3	76.5	160.08
2	28.8	68	3	76.5	189.39
3	35.2	68	3	76.5	162.33
4	32	61.2	3	76.5	190.63
5	32	74.8	3	76.5	150.23
6	32	68	1.5	76.5	151.57
7	32	68	4.5	76.5	185.41
8	32	68	3	68.85	162.89
9	32	68	3	84.15	160.68
10	29.747	63.211	1.9437	71.113	187.24
11	34.253	63.211	1.9437	71.113	169.25
12	29.747	72.789	1.9437	71.113	160.42
13	34.253	72.789	1.9437	71.113	144.07
14	29.747	63.211	4.0563	71.113	224.64
15	34.253	63.211	4.0563	71.113	180.79
16	29.747	72.789	4.0563	71.113	183.36
17	34.253	72.789	4.0563	71.113	156.8
18	29.747	63.211	1.9437	81.887	188.51
19	34.253	63.211	1.9437	81.887	165.84
20	29.747	72.789	1.9437	81.887	154.64
21	34.253	72.789	1.9437	81.887	158.8
22	29.747	63.211	4.0563	81.887	213.72
23	34.253	63.211	4.0563	81.887	180.38
24	29.747	72.789	4.0563	81.887	181.68
25	34.253	72.789	4.0563	81.887	158.08

Table 2: Three groups of design variables corresponding to the minimum stress on the slips

A	B	C	D	E	F
Candidate points	P1-plane4.L2 (mm)	P2-Extudel.FD1 (mm)	P3-Fblend.FD1 (mm)	P5-plane.L5 (mm)	P4-Equivalent stress maximum(Mpa)
Candidate A	33.632	72.424	2.1446	69.294	145.14
Candidate B	32.352	73.806	2.5891	69.783	146.89
Candidate C	32.864	74.656	1.7002	79.575	147.22

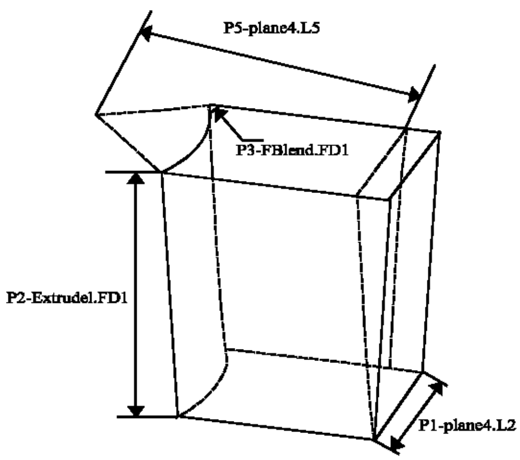


Fig. 4: Mathematics model of optimization size

If the goal equivalent stress is set small and the importance degree is set high, three set of optimum solutions were obtained, which are shown in Table 2.

In order to determine the most suitable parameters, it is necessary to study the relationships between the greatest stress and each parameter. The relationships between the greatest stress and each parameter are given in Fig. 5a-d.

From Fig. 5a, when the width of the slips is 33.7 mm, the stress of the slips is the minimum and the stress increases as the width vary from 33.7 mm.

The optimum value of width should also depend on the slope.

For the height of the slips Fig. 5b, the stress of the slips decrease as it increases. When it is larger than 74 mm, the stress does not change.

In Fig. 5c, the stress of the slips shows descending trend with increasing value of the sideline chamfering of slips as the sideline chamfering is smaller than 1.7 mm. While as it is larger than 1.7 mm, the stress increases with the increasing value of the sideline chamfering. The stress concentration normally occurs at the contact region between the slips and the drill pipe, so the sideline chamfering should be set larger value.

It was found from Fig. 5d that the stress of the slips is not influenced by distance from arc center to base line, because the slips act as force carriers (two-force beam elements) when the drill pipe is clamped by the slips.

Therefore, based on the relationships between the greatest stress and each parameter, the first group of

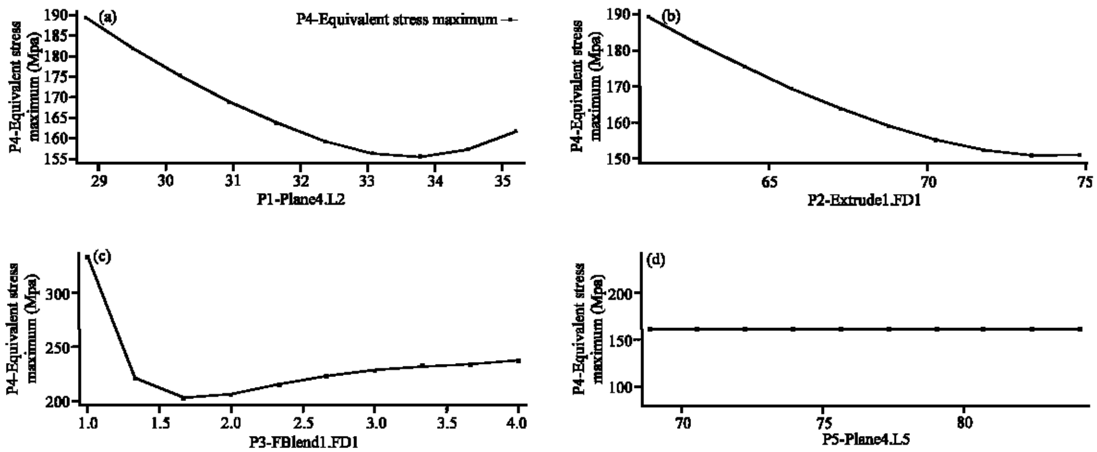


Fig. 5(a-d): (a) The curve of the greatest stress changed with the width of the slips, (b) The curve of the greatest stress changed with the height of the slips, (c) The curve of the greatest stress changed with sideline chamfering of the slips, (d) The curves of the greatest stress changed with distance from arc center to base line of the slips

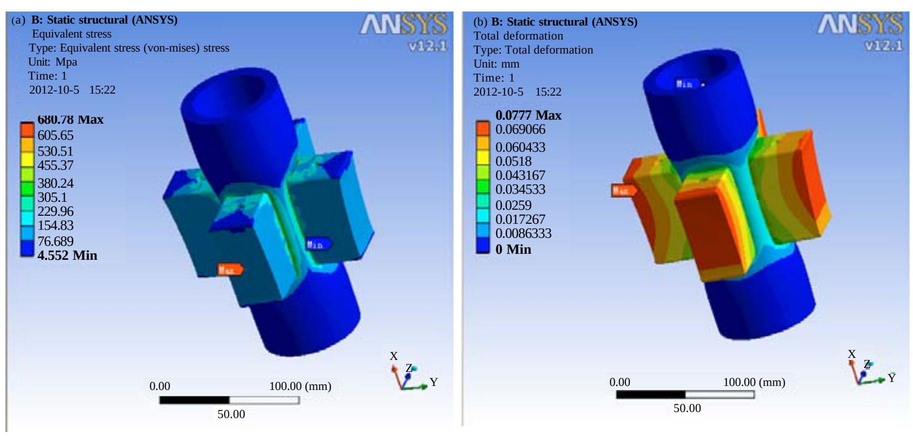


Fig. 6(a-b): (a) The coupling stress diagram of the optimized slips in the state of the full hydraulic chuck clamping a drill pipe, (b) The coupling strain diagram of the optimized slips in the state of the full hydraulic chuck clamping a drill pipe

optimum solutions was chosen. The values were rounded to the nearest integer and put into the calculation of the static analysis of the slips again. The obtained stress-strain diagrams are shown in Fig. 6a and b.

From the above diagram, it can be seen that the maximum stress in the assembly is still the place where the slips contact with the drill pipe. The maximum stress is 680 Mpa which is less than the yield limit of both the drill pipe and the slips. Comparing with the previous analysis, the maximum stress becomes smaller. As a whole, the intensity of clamp is reasonable, which means that the optimized size of the slips can meet the design requirement better.

CONCLUSION

Taking the diameter of pipe 73 mm as example, the structure of a full hydraulic chuck was presented. The interaction mechanism between the slips and the drill pipe has been investigated emphatically. Through the finite element analysis, simulation analysis and optimization design were carried out on the clamp mechanism and slips. According to the study, it obtained a set of optimum size for the full hydraulic chuck and drew the following conclusions:

- Stress of the slips is the minimum as the width of the slips is 33.7 mm and the stress increases as the width vary from 33.7 mm
- Stress of the slips shows descending trend as the height of the slips increases. As the height is larger than 74 mm, the stress keeps invariant
- Stress of the slips decreases with the increasing value of sideline chamfering of slips as it is smaller than 1.7 mm; while, as the sideline chamfering is larger than 1.7 mm, the stress increases with the increasing value of sideline chamfering. The stress concentration normally occurs at the contact region between the slips and the drill pipe, so the sideline chamfering should be taken larger value
- Stress of the slips is not affected by the distance from arc center to base line because the slips are just force carriers when the drill pipe is clamped by the slips

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