Mechanical Design of Downhole Tractor Based on Two-Way Self-locking Mechanism

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Abstract. Based on the technology of horizontal well tractor, a kind of downhole tractor was developed which can realize Two-Way self-locking function. Aiming at the needs of horizontal well logging to realize the target of small size, high traction and high reliability, the tractor selects unique heart-shaped *CAM* as the locking mechanism. The motion principle of telescopic downhole tractor, the design of mechanical structure and locking principle of the locking mechanism are all analyzed. The mathematical expressions of traction are obtained by mechanical analysis of parallel support rod in the locking mechanism. The force analysis and contour design of the heart-shaped *CAM* are performed, which can lay the foundation for the development of tractor prototype.

1. Introduction

In recent years, the method of drilling horizontal wells and enhancing horizontal well length to increase oil and gas recovery factor has become an important way to increase production of oil and gas[1-2]. However, the development of large displacement horizontal well has raised higher and higher requirements for logging and other underground operations and traction technology of supporting instrument[3]. Well logging can't be placed into a horizontal well relying on gravity, and the logging instruments must overcome the devolution caused by the hole bending. For this kind of demand, the technology of horizontal well tractor has been studied extensively[4-5].

At present, there are various types of downhole traction robot. Based on the different driving modes, the tractors can be mostly divided into four types: the telescopic downhole tractor, the wheel type downhole tractor, high pressure jet downhole tractor and propeller propelling downhole tractor[6]. In the late 1990s, many companies in foreign countries developed horizontal well tractors capable of working independently in the mine[7]. In many products, the wheel type tractor developed by Statoil, Maritime Well Service (MWS) and Welltec 3 companies jointly, telescopic downhole tractor produced from SmarTract and the Sondex horizontal well tractor are most prominent[8].

This paper presents a kind of downhole tractor which can realize two-way self-locking function, based on the technology of horizontal well tractor and the locking principle in the retractable micro-pipe robot. The tractor selects unique heart-shaped *CAM* as the locking mechanism, aiming at the needs of horizontal well logging to realize the target of small size, high traction and high reliability. Firstly, the motion principle of telescopic downhole tractor is introduced in this paper. Then, the design of mechanical structure and locking principle of the locking mechanism are analyzed. The mathematical expressions of traction are obtained by the mechanical analysis of parallel support rod in the locking mechanism. Finally, the force analysis and contour design of the heart-shaped CAM are performed, which can provide the basis for the design and manufacture of the prototype of the tractor locking mechanism.

2. Motion Principle of Downhole Tractor

The basic motion unit of the tractor based on the two-way locking mechanism consists of two locking mechanisms and a telescopic actuator. The motion principle is shown in figure 1. Figure 1 (a) is the initial state, and the supporting arms of the two locking mechanisms are propped up and pressed against the wall. Then the telescopic mechamism expands, and the locking mechanism 1 locks and the front locking mechanism 2 unlocks, so the locking mechanism 2 is pushed forward, as shown in figure (b). Telescopic mechanism begins to bounce back after spreading to the back of range, the locking mechanism 2 in front locks. The locking mechanism 1 unlocks, and its body is drag to move forward, as shown in figure (c), When the above procedure is completed, the tractor returns to a state in figure 1 (a), and the system has been running forward a distance at this time. Repeating movement process of from figure (a) to figure (c), tractor will be able to move forward.

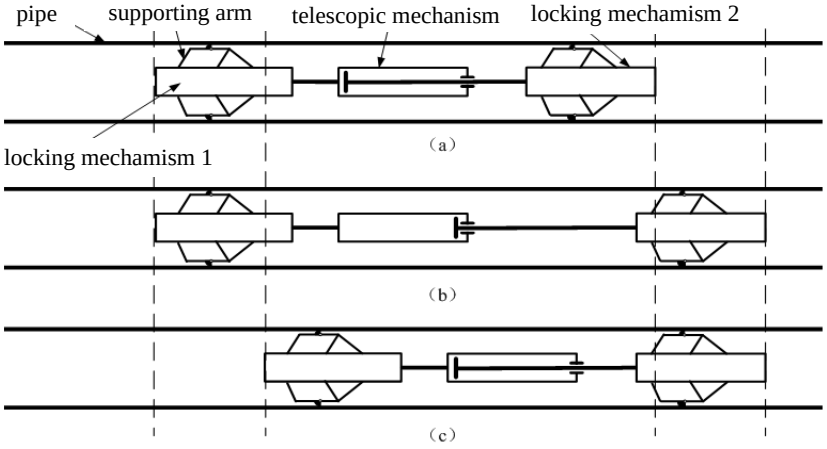


Figure 1 Motion principle of telescopic tractor

3. Design and Mechanical Analysis of Locking Mechanism

3.1 Design of the Two-way Locking Mechanism

The underground pipeline is filled with oil, sediment and so on. The realization of the telescopic tractor function has to set reasonable stress points, which is the use point of the supporting force of the tractor. In order to find the stress point in this complex environment, the two-way locking mechanism is designed. The locking mechanism is a key module that affects the ability of the tractor to function normally. Its function is to make the tractor only move in one direction, and the other direction is stuck. The schematic diagram of two-way locking mechanism is shown in figure 2.

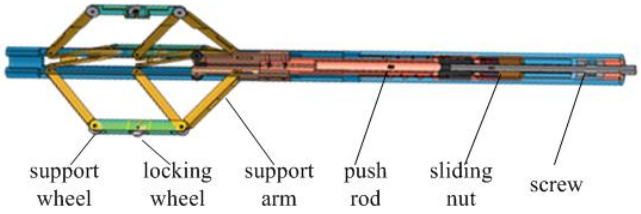
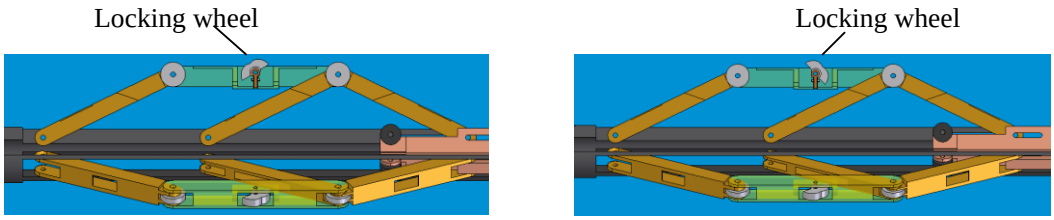


Figure 2 Schematic diagram of two-way locking mechanism

The heart-shaped locking wheel starts to work when the support wheel moves to the wall. The locking of different directions can be realized, if the heart-shaped locking wheel is in the different initial position. As shown in figure 3 (a), the initial position of the locking wheel is shown, When the tractor is moving to the left, the heart-shaped locking wheel turns clockwise, the contact force between the *CAM* and the wall is reduced, friction is reduced, and the tractor can move forward by overcoming the force of friction. When the tractor is moving to the right, the heart-shaped locking wheel turns counterclockwise, the contact force of the *CAM* and tube wall is increased, the contact force is increased, the mechanism locks. Similarly, as shown in figure 3 (b), the mechanism can achieve the right movement and the left locking movement.



（a）left movement, right locking （b）right movement, left locking

Figure 3 Locking principle of two-way locking mechanism

3.2 Mechanical Analysis of Parallel Four-bar Mechanism

The forces of the parallel four-bar mechanism are shown in figure 4. The external forces of the mechanism are: N is the contact force of self-locking mechanism and pipe wall, fu is the friction force of self-locking mechanism and pipe wall, and F_s is the force of screw rod.

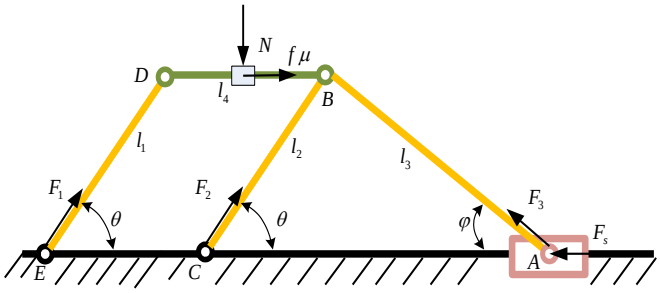


Figure 4. The force diagram of the four-bar mechanism

According to the tractor motion conditions, the friction force of the mechanism must be greater than the traction force,

$$fu \geq F_s \tag{1}$$

In the case of an expanding mechanism, the hypothetical equation (1) is satisfied, according to the force equilibrium condition,

$$\begin{cases} N = F_1 \cdot \sin\theta + F_2 \cdot \sin\theta + F_3 \cdot \sin\phi \\ fu + F_1 \cdot \cos\theta + F_2 \cdot \cos\theta = F_3 \cdot \cos\phi \\ F_1 \sin\theta = \lambda(F_2.\sin\theta + F_3.\sin\phi) \end{cases} \tag{2}$$

Applied the force balance condition of the ball screw，

$$F_S = F_3 \cdot \cos\phi \tag{3}$$

Combined (2) and (3), the forces of each support rod are

$$\begin{cases} F_1 = \dfrac{\lambda \cdot N}{(\lambda+1)\sin\theta} \\ F_2 = -\dfrac{N(-\sin\theta \cdot \cos\phi + \lambda \cdot \sin\phi \cdot \cos\theta + \sin\phi \cdot \sin\theta \cdot f\mu + \lambda \cdot \sin\phi \cdot \sin\theta \cdot f\mu)}{\sin\theta(\lambda+1)(\sin\theta\cos\phi + \cos\theta\sin\phi)} \\ F_3 = \dfrac{N(\sin\theta \cdot f\mu + \cos\theta)}{\sin\phi\cos\theta + \cos\phi\sin\theta} \end{cases} \tag{4}$$

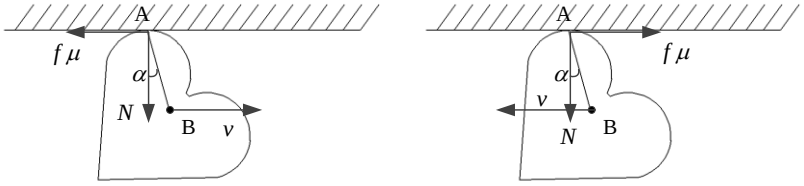
Applied geometrical relation, and the rod thrust is

$$F_S \geq \frac{(fu(R-r) + \sqrt{l^2 - (R-r)^2})\sqrt{l_3^2 - (R-r)^2}F}{(R-r)\,fu(\sqrt{l_3^2 - (R-r)^2} + \sqrt{l^2 - (R-r)^2})} \tag{5}$$

It can be seen that the driving force is related to the pipe wall pressure, the length of the drive rod and the length of the support rod.

4. Profile Design of Heart-shaped *CAM*

When the wheel the trend of right movement is shown in figure 5 (a), the friction *fu* and the positive pressure *N* make the same direction torque on the center of rotation *B*, which can make the heart-shaped wheel run away from the wall.



(a) the trend of right movement (b) the trend of left movement

Figure 5 Schematic diagram of the heart-shaped wheel

The heart-shaped wheel should be stuck, when it has the left movement trend as shown in figure 5 (b). Therefore, the direction is shown in Figure 5 (b).

As shown in figure 6, the distance between rotating center *B* and contact point *A* is *R*, after the time of Δt, the contact point is point *D*, the turning angle is $d\theta$. *AC* is the tangent direction of the point *A* and perpendicular to the *AB*. Because $d\theta$ is very small, it can be considered that *AC* is perpendicular to *BD*, BA is perpendicular to *AD*.

Hence the following equation is found in triangle *ACD*,

$$\angle CAD = \angle\alpha$$

$$\tan\alpha = \frac{DC}{AC} \tag{6}$$

Where, $DC = d\rho, AC = \rho \bullet d\theta$,

$$\tan\alpha = \frac{d\rho}{\rho \cdot d\theta} \le \mu \tag{7}$$

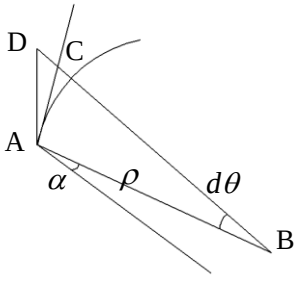
The contour curve of heart-shaped wheel is

$$\theta = \frac{1}{\mu} \bullet \ln\frac{\rho}{\rho_0} \tag{8}$$

The maximum height of the mounting bracket is 19mm, and $\mu = 0.25$. The minimum distance of the center to the horizontal line is 1*mm*. Solved equation,

$$\begin{cases} \rho \bullet \cos(\pi - \theta) = 6 \\ \theta = 4 \bullet \ln\dfrac{\rho}{15.53} \end{cases} \tag{9}$$

The optimal contour line of the heart-shaped locking wheel is shown in figure 7.



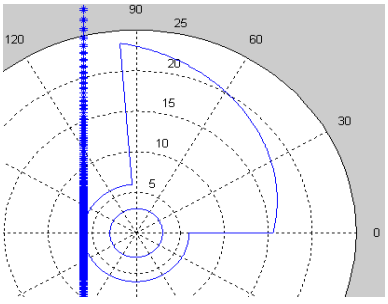


Figure 6 Diagram of heart-shaped shape **Figure7**. Contour of heart-shaped wheel

5. Conclusion

In this paper, a kind of downhole tractor was developed which can realize Two-Way self-locking function. The tractor selects unique heart-shaped *CAM* as the locking mechanism, which can meet the requirement of small size, high traction and high reliability. The motion principle of telescopic downhole tractor, the design of mechanical structure and locking principle of the locking mechanism were all analyzed. Finally the force analysis and contour design of the heart-shaped *CAM* are researched, which is helpful to develop the tractor prototype.

References

[1] A. Shukla, H. Karki, Application of Robotics in Onshore Oil and Gas industry, A review Part I, Robotics and Autonomous Systems, vol. 75, 2016, pp. 490–507.
[2] J. S. Cao, L. Lin, Y. Li, Research and Development Progress in Oil and Gas Pipeline Robotics, Oil & Gas Storage and Transportation, vol. 32, 2013, pp. 1-7.
[3] S. Roh, H. R. Choi. Differential-Drive In-pipe Robot for Moving Inside Urban Gas Pipelines [J]. IEEE Transactions On Robotics, 2005, 21(1): 1~17.
[4] Zheng T , Godage IS , Branson DT , Kang R , Guglielmino E , Medrano-Cerda GA . Octopus inspired walking robot: design, control and experimental validation. In: Robotics and automation (ICRA), 2013 IEEE international conference on. IEEE; 2013. pp. 816–21 .
[5] L. Q. Li, D. K. Zhou, G. Y. Zhang, Y. Q. Li, W. P. Song, Optimal design of horizontal well traction robot traction force regulating mechanism. Advanced Materials Research, vol. 1033, 2014, pp. 1350-1353.
[6] S. Gao，W. Sun，H. Ni, “Status and understandings of downhole tractor design”, Journal of Machine Design, vol. 31, 2014, pp. 1-8.
[7] Stolte C, Wu C, Carroll D, et al. Coiled tubing and well test experiences on sichuan horizontal shale gas wells[C]// International Petroleum Technology Conference, Beijing, China, March 26–28, 2013: 1–5.
[8] Billingham M, Etoukhy A M, Hashem M K, et al. Conveyance—down and out in the oil field[J]. Oilfield Review, 2011, 23(2): 18–31.

Acknowledgments

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