Acta Technica 62 No. 2B/2017, 307–318

Design of detection robot of fault oil well[1]

Hangxin Wei[2,3], Wei Wu[2], Wenkui Xi[2]

Abstract. The exploration instrument is very important for the breakdown maintenance of the production of oil wells, and it can help to understand the internal conditions of the oil wells. However, the traditional detection robot can not adapt to the complicated channel environment and realize the function of detection in the well. The combination of traditional pipeline robot was used for the design of a new detection robot of fault oil well, and virtual simulation technology was used to design the structure of key parts, and the robot hydraulic system and the state of force in different states were calculated respectively. Finally, through the test, the force test of the pipeline robot's performance was carried out. It is proved that the robot can satisfy the demand of the movement and the force, which provides some reference for the design of detection robots of fault oil well in our country.

Key words. Pipeline detection, robot, kinematics, oil well.

1. Introduction

Oil well is an important production device for oil and gas exploitation, and the radial size is small and the depth degree is into the ground. According to their different types, the oil wells can be divided into oil wells, gas wells and injection wells [1]. With the continuous development of China's economy, a large number of oil-related resources have been mined. According to statistics, by the end of 2006, China has developed more than 100 thousand oil wells in service. According to different operations, the production unit of oil and gas can be divided into the production operation well and the fault operation well [2]. Among them, the fault operation wells refer to the oil wells which are in fault, and these oil wells need troubleshooting. In our country, about 1/3 of the oil wells have faults every year, and they need to be repaired so that they can continue to ensure that the well can

[1]This work reported in this National natural science foundation of China, Study on multidisciplinary collaborative design modeling and deep knowledge acquisition for high parameter rotor system with coupled flow force and small clearance force, No. 51405385.

[2]School of Mechanical Engineering, Xi'an Shiyou University, Xi'an, Shanxi, 710065, China

[3]Corresponding author

carry out the normal production operation smoothly [3].

The oil wells still rely mainly on water flooding in China: it raises the pressure by injecting water into the ground, thus eventually getting the resources we want. However, due to the complex underground environment and difficult judgment on the geological condition, it is easy to cause serious faults, which makes workover operations more important [4]. Now, when downhole operations are performed, it is often possible to use the cables to put the detected instruments and operating equipment into the well, but under self-weight, this can only be done with simple ascending and descending operations [5]. The downhole production or maintenance operation of the oil well can be carried out in a timely and accurate manner through the downhole video detection system, and it also can distinguish and detect the inside of the well [6]. In order to further expand the ability of downhole detection instruments, improve the accuracy and effect of downhole detections, and accurately determine the type and situation of downhole faults, the design of the fault oil well robot is carried out to realize the intelligent detection of the downhole fault.

2. State of the art

Cable power is still the main power source of the existing downhole detection equipment, which uses its own motor or fluid as the power and relies on the inertial navigation robot to realize the active walking in the well, and the robot sends the relevant instruments to the correct position [7]. The downhole robot has been used as a downhole tractor or downhole retractor, and according to their different driving modes, they can be divided into wheeled downhole tractor, telescopic downhole tractor, high-pressure jet recoil downhole tractor, and propeller downhole tractor [8]. In 2000, Smart Tract developed a retractable cable tractor that was the most new type of tractor at that time and it could be operated in double ways [9]. This kind of tractor is not only larger in size than moving through the urine, but also requires less power, and the ground equipment is very compact, which is easy to operate specific engineering applications. Sondex Company has also developed a wheeled cable tractor that is much different from the conventional tractor, which uses a non-hydraulic pump. The maximum outer diameter is 54 mm and the maximum pulling force is 2.68 kN, and the bidirectional drive can be realized, and this tractor has been perforated in Southeast Asia to recover remaining oil deposits [10]. "Bore-shuttle" and "Baker-Hughes" downhole robots of Shell Oil Company can completely be operated autonomously, which can realize the tube walking of robots by using the built-in power source [11]. Based on pipeline robot, fault detection technology and application in oil well can be further improved, and new fault detection technology of robot in fault well is developed [12].

3. Methodology

3.1. Conceptual design of robot

The research robot can realize the free intelligent walking in the complex environment of the oil well, and it is possible to detect the conditions in the well. Based on the design idea of the existing oil well exploration robot (as shown in Fig. 1), this detection robot mainly consists of hydraulic components, electrical components, components that support upper and lower and detection components. The hydraulic components are connected together to the components that support walking, and they form a closed-type system together, which is the control unit and drive unit of the whole components that support walking. The pressure compensated fuel tank is designed because of adopting the variable amplitude supercharging mode, and with the increase of the depth of the robot and the increase of the well fluid pressure, the tank pressure in the robot will also rise, and the working pressure of the whole hydraulic system is a variable pressure working state. The electrical components of the robot are in the rear position, and are mainly composed of communication components, electrical control components, and drive motors, which can realize the signal transmission, power transmission and power control of the robot with the ground during the downhole operation.

Fig. 1. Common pipe robots

The detection module is located at the front end of the detecting robot. In this selection of conventional ultrasonic imaging and other detection instruments, more advanced downhole video detectors can be installed as required. The components that support walking and the detecting components are connected together, which is an important execution part of the mobile carrier of the robot, and it adopts the hydraulic driving mode. The driving principle of this kind of drive is the slip piston type, and when the robot moves through the well, the upper and lower supporting components will move, loosen, extend and shrink alternately. The walking component with upper and lower support adopts a universal hinge joint, thus, the robot can achieve the horizontal or directional wells of different directions in the well.

3.2. Hydraulic system design of fault detection robot in oil well

The hydraulic system of the robot is designed with a closed hydraulic system, and the pressure compensating tank is operated with variable amplitude supercharging. With the increasing depth h of the robot in the well, the fluid pressure P_1 of the well will also increase gradually, and correspondingly, the pressure in the tank is gradually increasing. The pressure in the tank is greater than or equal to the hydraulic pressure of the well, and the hydraulic pump pressure is ΔP. From this it can be seen that the working pressure of the pump is equal to the sum of P_1 and ΔP. In the process of operation, when the oil flow in the hydraulic circuit, there will be a certain pressure loss, and coupled with the pressure damage of the pipeline and each valve, the total pressure loss of the whole oil circuit is $P_{\mathrm{s}} = 1\,\mathrm{MPa}$.

The structural representation of the support cylinder is shown in Fig. 2. It is assumed that inner diameter and the cross sectional area of the support cylinder are, respectively, $S_1\,, D_1$, the outer diameter and cross sectional area of the piston rod are $S_2\,, D_2$, and the left cross section of the piston is $\Delta S = S_1 - S_2$.

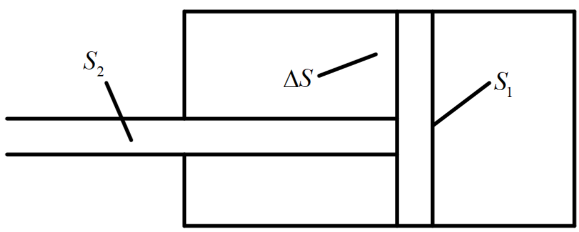

Fig. 2. Chart of the support hydraulic cylinder

As the piston advances to the right, the force acting on the left and right end of the piston is shown in the formulas

$$F = P\Delta S = (P_1 + \Delta P - P_{\mathrm{s}})\,\Delta S \tag{1}$$

and

$$F = PS_1 = P_1 S_1\,. \tag{2}$$

Then the force acting on the piston rod by the well fluid can be calculated as

$$F = P_1 S_2\,. \tag{3}$$

The force analysis and calculation formula of the whole piston is

$$F = (P\Delta S_1 - PS_1)\,\eta_{\rm m} + P_1 S_2 \approx (\Delta P - P_{\rm s})\,\Delta S\,. \tag{4}$$

The minimum force required to support the cylinder piston and the minimum card effort required for the support foot are both greater than the maximum load that the piston receives. The main dimensions of the walking cylinder are shown in Fig. 3. It is assumed that the inner diameter and the cross sectional area of the walking cylinder are respectively $D_3\,, S_3$, and the outer diameter and cross sectional area of the piston rod are $D_4\,, S_4$. Thus, the left cross section of the race can be obtained in the form $\Delta S' = S_3 - S_4$.

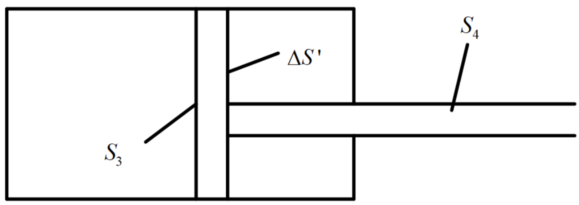

Fig. 3. Chart of move of hydraulic cylinder

As the piston advances to the right, the force of the piston's left and right ends is shown in formula (5) and formula (6), separately:

$$F = PS_3 = (P_1 + \Delta P - P_{\rm s})\,S_3\,, \tag{5}$$

$$F = P\Delta S' = P_1 \Delta S'\,. \tag{6}$$

Then the force acting on the piston rod by the well fluid is

$$F = P_1 S_1\,. \tag{7}$$

The force analysis and calculation formula of the whole piston is

$$F_1 = (PS_3 - P\Delta S')\,\eta_{\rm m} F \approx (\Delta P - P_{\rm s})\,S_3\,. \tag{8}$$

In summary, combined with the design parameters, the flows, pressures and power values of the hydraulic cylinder at different stages are shown in Table 1.

3.3. Structural design of fault detection robot for oil wells

The operating conditions in the pipeline are relatively complex, which requires that the detection robot must be flexible, so the shell of the robot is composed of 2 cylinders. The robot uses a wheeled carrier, with 3 sets of support wheels that are uniformly distributed in the circumferential direction of the pipe, and the wheel telescopic mechanism is used to ensure that the support wheel can be extended and changed within the range of 300 mm$\sim$400 mm in the pipe diameter, and the tight joint of the support wheel and the pipe wall can be realized by using the torsion spring. Among them, the first section of the cylinder is instrument cabin, and the second section is the battery cabin. The instrument cabinet contains modules such as signal acquisition, data storage, electrode drive, etc., and the battery compartment contains batteries for the entire instrument. With the joint of the universal joint, the second section of the cylinder is more flexible, so that the robot can walk better. The casing of the robot is nested and linked together, including a clamping cylinder and a walking cylinder, and all the valves are embedded in the shell of the robot, and the hydraulic circuit of the robot is also completed inside the shell.

Table 1. Pressure, flow and power value of hydraulic cylinder in different stages

Working condition		Load	Oil return chamber pressure	Inlet chamber pressure
Support cylinder	Fast forward	$-P_1S_2$	P_1	P_1
	Feeding	$F - P_1P_2$	P_1	$P_1 + \Delta P - P_s$
	Rewind	P_1S_2	P_1	P_1
Walking cylinder	Fast forward	P_1S_3	P_1	P_1
	Rewind	$F - P_1S_3$	P_1	$P_1 + 10^3F$

The clamping cylinder and the end cover of the running cylinder are connected to the cylinder by welding, and end caps on the rod side of the hydraulic cylinder are connected with the cylinder when the outer thread is used, but the rear end cap still uses a welded joint. Through this connection, it is possible to reduce the exposure of various parts of the cylinder as far as possible, so as to ensure the smaller size and smooth appearance, and it can improve the robot's bearable impact load to a certain extent and adapt to more adverse external environments. In the design of the piston structure, the slip ring combination of piston - car foot type is selected, and the direct guide sleeve of end cap type is used at the outer end of the piston rod. The virtual design of the pipe robot is shown in Fig. 4

3.4. Kinematics analysis of fault detection robot for oil wells

Because the environment in the oil well is complex, the requirement on the performance of the fault detection robot is higher. The main factors that influence the performance include the robot's supporting foot, clamping force, traction force and piston thrust, which affect the stability and flexibility of the robot walking in the mine. Among them, the traction force determines the robot's walking ability, and the size of the supporting foot of the robot is affected by the thrust of the piston, and there is a certain mathematical relationship between the two. Figure 5 illustrates the force diagram of the supporting foot, and then uses a simple mathematical model to represent the mathematical relationship between the three parameters. From their mathematical relationship, it can be seen that the traction force of the robot is pro-

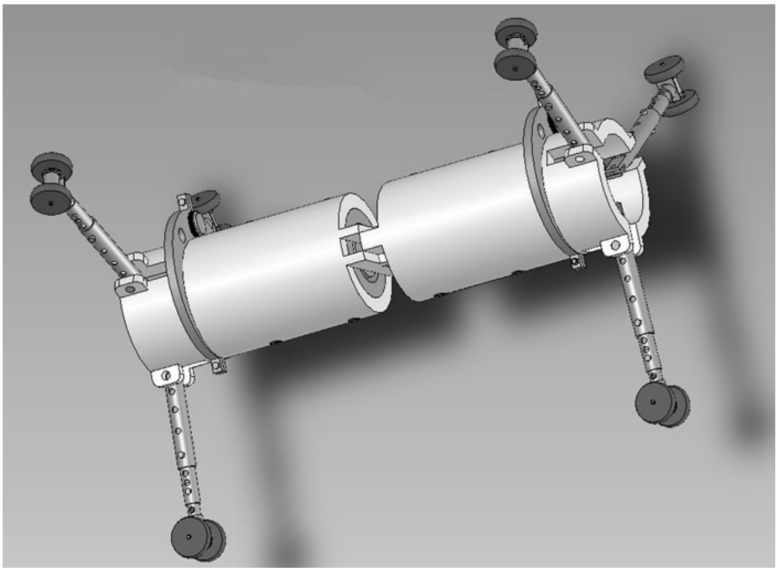

Fig. 4. Virtual modeling of pipeline robot

portional to the supporting force of the foot, that is, the increase in the clamping force of the foot will increase the traction of the robot accordingly.

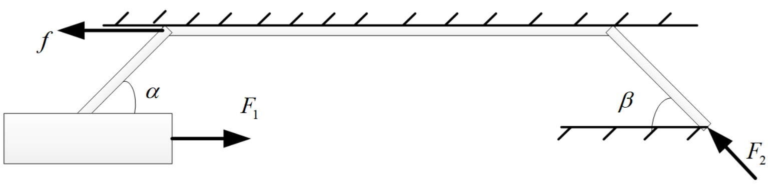

Fig. 5. Force diagram of robot's feet

When the diameter of the borehole is in the range of 90 to 130 mm, the stability of the robot walking will also decrease as the bore diameter becomes smaller, similarly, as the cable drag increases, the stability of the robot will also decrease. The fault detection robot of oil well can keep relatively stable running state when walking in vertical shaft, and the single walking distance can reach 160 mm, and the average walking speed is 7.1 mm/s. Under the pulling force of the cable, the robot will be locked between the support foot and the shaft lining, however, the self-locking will decrease with the decrease of the bore diameter, which will lead to lower stability. Taking the walking of the fault detection robot in the well with an inner diameter of 90 mm as an example, when the pulling force of the cable reaches 5 kN, the support foot of each walk will slide 10 mm to ensure the stability of the robot while walking in the well.

The upper and lower support legs of the robot are clamped to the shaft wall to ensure its stability, but as the robot moves, this clamping force will change slightly. Because of the impact of the weight of the robot, the force of the lower support foot varies greatly, and contact forces between the support foot and the shaft wall will also change a little, so this change is directly reflected in the specific stress changes. When the support leg of the robot is clamped in the shaft wall, the cylinder piston force under its support is 3 kN, and its range of change is 2.7–3.3 kN, which is due to the fluctuation of the piston force caused by the change of the foot clamping force.

4. Results analysis and discussion

4.1. Environment condition

The modular design of the detection robot for the fault oil well is shown in Fig. 6. The robot uses a three-axle differential type, and its main parameters are: the mass of the robot is 26 kg, the normal running speed is 80 mm/s, the axial length is 0.55 m, the pipe diameter is 0.31 m, the input power is 120 W, and the output tractive force is 0.24 kN.

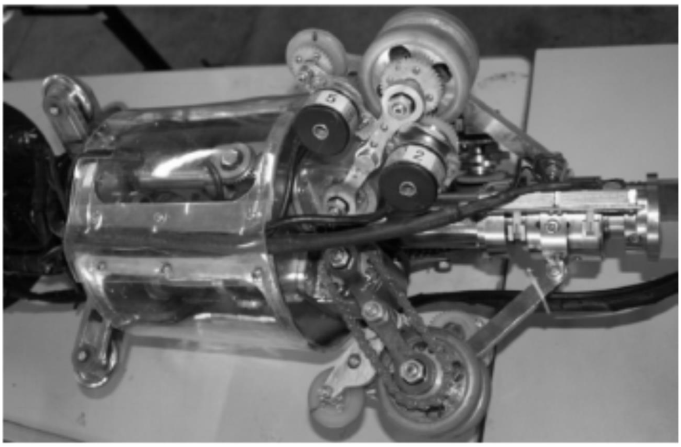

Fig. 6. Pipeline robot prototype

A test tube of the robot is made of a steel tube and an organic glass tube which is connected by flanges, and the inner diameter and outer diameter of the pipeline are 0.31 m and 0.325 m respectively. The material of the bent pipe in the pipe is a steel tube, while the straight pipe is made of plexiglass tube, and the radius of curvature is 0.93 m.

4.2. Robot test

Speed sensor was installed at the driving wheel and driven wheel, and through the measured results, the running speed was compared and analyzed, so as to determine whether the robot is locked, turned or skidded during the operation. The robot was set to move into the bent pipe according to different attitude angles. The walking test shows that the robot can smoothly pass through the elbow. Further comparison and analysis of the relative data show that the driven wheel has better following effect, and slipping and motion interference do not occur in the driving wheel. During the operation of the elbow, the robot walks at a uniform speed, and its smooth walking shows that the three-axis differential actuator plays a good role in differential regulation.

The differential effect of the robot attitude angle of 0° and 30° in the operation of the elbow was analyzed respectively. When the attitude angle was in 0°, the curve of the angular speed of the driving wheel was obtained, as shown in Fig. 7. Furthermore, the average angular velocity of the drive wheel and the result of the theoretical calculation were compared and analyzed during the operation of the bent pipe, and at the same time, the error analysis was carried out. By comparing and analyzing the results, it can be seen that the analysis results of the two are equal and the error is quite small, which further shows that the robot has very good differential speed effects.

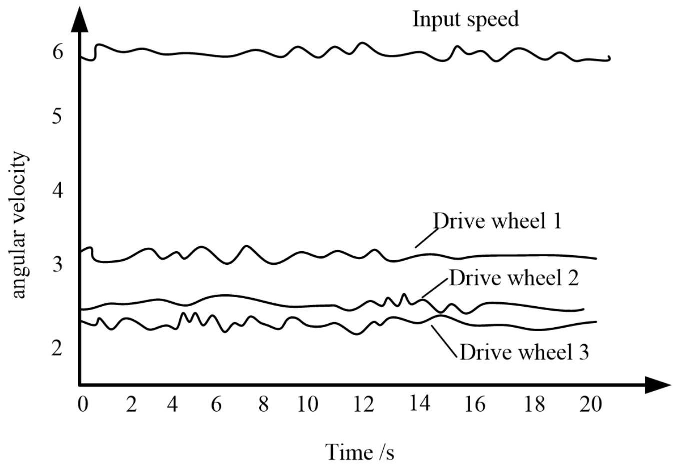

Fig. 7. Angular velocity curve of driving wheel

4.3. Traction test of robot

In order to ensure the stability of the load during the test and the real-time adjustment function, a robot's end pipe friction tester was used to provide the load. The traction test of the robot was carried out in the plexiglass tube section. The preload of the robot was set at 0.35 kN, and its initial speed was 0.08 m/s. When the load was loaded to 0.24 kN, the robot could still run normally, and the robot did not slip during the operation.

The maximum traction test of robot under different preload was carried out, and the friction tester was locked, so that the robot's drag force could be run by sensors. When the driving wheel of the robot was slipping, the maximum tractive force of the corresponding robot could be measured under the action of the pull force. In the process of testing, the pretension was gradually increased, and the tractive force of the robot was gradually increased, but ultimately it was limited by the power rating of the drive motor, and when the preload increased to 0.5 kN, there was a stall phenomenon in the motor. The friction factor between the drive wheel and the tube wall was 0.8, and the included angles of the pretightening mechanism α and β were 44° and 42°, respectively. By comparing the theoretical and experimental values of the traction force under different pretensions, the maximum error was only 6.3 %. This shows that the experimental results are in good agreement with the theoretical results.

From the test results, it can be seen that the robot preload is the same as the result in the robot traction test with different attitude angles, and the maximum tractive force measured at the end is in good agreement with the theoretical result. It also shows that there is no significant relationship between the traction force and the attitude angle of the robot.

5. Conclusion

The fault oil well can be detected through the use of pipeline robot, which can walk autonomously in the well by carrying sensors or other operating devices, thus transmitting information from the well to the ground. Considering the size of the drive wheel and the attitude model of the robot running in the elbow, the shortcomings of the previous model were made up by the model that can be used as a general model for solving the position and orientation problem of the bent pipe of a robot, and the theoretical speed ratio relationship of the drive wheel was verified when the pipe was running. The bend test of the detection robot of fault oil well was carried out further, and results of each parameter measured by the test were compared with the results of the simulation analysis, so as to verify the performance of the robot. Through the test results, it can be seen that the robot can run smoothly in the bent pipe and meet the functional requirements, which coincides with the simulation results. Compared with the traditional detection robot, the robot has better stability and lower cost, so it has certain popularization values. But research on robot intelligence is relatively small, so it can strengthen the intelligence research of robot, thus further improving its performance.

References

[1] N. Mohamed, J. Al-Jaroodi, I. Jawhar: *A cost-effective design for combining sensing robots and fixed sensors for fault-tolerant linear wireless sensor networks.* International Journal of Distributed Sensor Networks *10* (2014), Article ID No. 659356, 1–11.

[2] S. Bhowmick: *An approach to design a simple human detecting robot for cost effective home security system as well as various rescue missions.* Communications on Applied Electronics (CAE), Foundation of Computer Science FCS *1* (2015), No. 8, 5–8.

[3] M. Van, H. J. Kang, Y. S. Suh, K. s. Shin: *A robust fault diagnosis and accommodation scheme for robot manipulators.* International Journal of Control, Automation and Systems *11* (2013), No. 2, 377–388.

[4] M. A. Kamel, X. Yu, Z. Zhang: *Fault-tolerant cooperative control design of multiple wheeled mobile robots.* IEEE Transactions on Control Systems Technology *PP* (2017), No. 99, 1–9.

[5] L. H. Zhang, Y. D. Chi, C. P. Board, J. P. Grid: *The research and design of overhead transmission line insulator detecting robot.* Electronic Design Engineering *23* (2015), No. 16, 164–166.

[6] J. Zhou, C. Huang, B. Liu, T. T. Wang: *A control system design of underwater robot for detecting underwater structures.* Applied Mechanics and Materials *536–537* (2014), 1105–1109.

[7] X, Tian, Y. Liu, Y. Zhang, R. Lin, Y. Xi: *Fault diagnosis research of submarine casing cutting robot for abandoned oil wellhead.* International Journal of Security and Its Applications *8* (2014), No. 1, 213–224.

[8] B. H. Wu, J. J. Xi: *Design and research of synchronous-style clamping mechanism for cable-detecting robot.* Advanced Materials Research *1028* (2014), 127–133.

[9] F. Xu, J. Hu, X. Wang, G. Jiang: *Helix cable-detecting robot for cable-stayed bridge: Design and analysis.* International Journal Robotics and Automation *29* (2014), No. 4, 406–414.

[10] B. Sun, B. Cai, Y. Zhang, Q. Fan, S. Yu: *Fault diagnosis research of submarine electro discharge cutting robot for abandoned oil wellhead.* Computer & Digital Engineering (2013), No. 7.

[11] H. W. Wang, X. N. Wang, X. Tian, G. H. Du, Y. M. Tian, q. M. S. Rong, W. K. Zhang: *Software and hardware design of a acoustic fault detecting instrument.* Applied Mechanics and Materials *432* (2013), 246–252.

[12] R. R. Kalia, P. Abrol: *Design and implementation of wireless live wire fault detector and protection in remote areas.* International Journal of Computer Applications *97* (2014), No. 17, 14–20.

Received August 7, 2017