Design of hydraulic driving experimental bench for automatic vertical drilling tool

Wenhui Yan¹, Heng Wu¹, Yinan Qu¹, and Yonghong Yan²

¹ Mechanical Engineering College, Xi’an Shiyou University, Xi’an 710065, Shaanxi, China;
² Institute of Baoji Oilfield Machinery Co., Ltd. Baoji 721002, Shaanxi, China
ywh369@xsyu.edu.cn.

Abstract. It’s introduced that the structure and function of automatic vertical drilling tool with independent intellectual property rights. The hydraulic driving experimental bench for automatic vertical drilling tool is a key experimental equipment, which is specially developed in the research and development of automatic vertical drilling tool. The experimental bench uses a water circulation system with centrifugal pump. It simulates the change of drilling fluid flow rate by frequency control. It uses an analog turnplate rotating device to simulate the working condition of the tool rotation. It introduces in detail the overall structure of the hydraulic driving experimental bench for automatic vertical drilling tool and the detail structure of the analog turnplate unit, the adjusting mechanism for analog hole deviation angle, and the testing unit for pushing force. The main technical parameters and design difficulties of the experimental bench are given in this paper. It has been proved in practice that the experimental bench can satisfy the functional test of automatic vertical drilling tool system.

1. Introduction
Aiming at the demands of vertical drilling technology on oil well, automatic vertical drilling tool is designed as a kind of drilling tool based on the principle of automatic control, which has the advantages about the high reliability on autonomous guidance, longevity and the high sensitivity. It can solve the problems of anti-deviation and fast drilling without reducing the normal drilling pressure.

The commercial automatic vertical drilling systems at abroad are mainly as follows: Schlumberger’s Power V system, Baker Hughes’ VertiTrak system and German Intelligent drilling Company’s Smart Drilling system, etc.

In recent years, automatic vertical drilling technology has been studied in China and some achievements have been acquired¹-⁴. Xi’an Shiyou University and Shengli Petroleum Administration Bureau jointly developed rotary steering drilling tools with independent intellectual property rights⁵-⁹. In addition, automatic vertical drilling tool with independent intellectual property rights have been developed jointly with Baoji Petroleum Machinery Co., Ltd¹⁰-¹⁴.

Automatic vertical drilling tool with independent intellectual property rights (hereinafter referred to as the tool) have been successfully developed after the overall design, unit experiments, hydraulic driving experiments, field testing and other stages. In order to carry out the unit experiment, the specially developed experimental bench includes turbine generator function test bench, stabilized platform function test bench, tool hydraulic driving experimental bench and so on. This paper mainly introduces the structure, technical parameters and technical difficulties of two tools. One is the
automatic vertical drilling tool, the other is the hydraulic driving experimental bench specially developed for testing the tool’s comprehensive performance.

2. The Structure and Functions of the Tool

2.1. The Structure of the Tool

The structure of automatic vertical drilling tool is shown in Figure 1. This tool is composed of power unit, measure-control-storage unit, suspension structure unit and executive unit, and is connected with MWD short section and drill bit by its top and bottom screw thread respectively. The key technologies of whole system include high sensitive measurement of well deviation, azimuth and toolface azimuth, high accuracy control of toolface azimuth, and fully sealed suspension support structure of rotating control shaft.

The power unit is mainly composed of turbine generator driven by mud. Due to the particularity of working conditions and environment, its special structure is different from common generator. Measure-control-storage unit consists of three parts: measurement, control and storage. The whole sensor and relevant circuit are installed in a closed compartment of the electronic cartridge, which synchronize to rotate or stabilize with control shaft during the work. The suspension supporting unit is mainly composed of upper and lower bearing sets, supporting the whole electronic cartridge and the control shaft, which is in the hanging condition. And the axial force is resisted by the up bearing. The bearings are sealed fully and no mud can through it. The structure of integral assembling with optimum type of bearing and relevant parameters ensures minimal friction torque of bearing. The structure ensures that the control shaft belongs to the integral assembly form and optimizes the bearing form and relevant parameters, in order to ensures the minimum friction torque of the bearing. Executive unit consists of columnar distributing valve, thrust plate and plunger. Figure 2 shows an automatic vertical drilling tool engineering prototype.

2.2. Functions and Main Technical Parameters of the Tool

The main functions of automatic vertical drilling tool are as follows: through the autonomous guidance technology of the system, it needs to ensure the largest inclination doesn’t exceed $1.5^\circ$ on the straight wellbore in case of keeping the normal drill pressure. In the process of development, new ideas, new
technologies and materials have been adopted, the working principle is essentially different from normal deviation control tool, the force for hole straightening is enough to resist the natural deflecting force in the stratum. Figure 3 shows the control schematic diagram of automatic vertical drilling tool.

Figure 3. The control schematic diagram of automatic vertical drilling tool.

Small closed loop control: Realization of small closed-loop control by the tool in the downhole. Hole deviation angle and azimuth are measured by measure unit, then the parameters are compared with the preset parameter of trajectory by downhole CPU. For example, if deviation exceeds the prescribed limit, according to the measured hole deviation angle, azimuth, toolface azimuth, rotation rate of the control shaft and load current, small closed loop control order and the control principle, the executive mechanism unit will act to adjust the tool position (toolface azimuth points to the specified location). If the deviation does not exceed the prescribed limit, the executive mechanism unit executes the original motion (the uniform velocity of control shaft is different from collar's).

Large closed loop control: The large closed loop control is composed of mud, MWD, ground control center and the tool. While small closed loop control in the downhole acts, the hole deviation angle, azimuth, toolface azimuth can be measured by MWD, which also can be transmitted to the ground control center, if deviation exceeds the prescribed limit, the tool will conduct the process correction and state judgment according to the principle of drilling technical parameters by the method such as reducing drill pressure, velocity, etc. If the deviation does not exceed the prescribed limit, the executive mechanism unit executes the original commands.

Main technical parameters of automatic vertical drilling tool are as follows:
- Well depth: ≤4000 m
- Operating pressure: ≤75 MPa
- Rpm: 60~200 r/min
- Applicable mud displacement: 20~45 l/s
- Total length of the tool: ≤6 m
- Tool outside diameter: Φ311 mm
- Tool pressure drop: ≤1 MPa
- Inclination control: ≤1.5°
- Maximum drill pressure: 300 kN
- Bit pressuredrop: ≥3 MPa
- Lateral thrust: ≥15 kN
- Increasing drilling speed: ≥50%
- Time between failures: ≥200 h
- Turbine generator rated speed: 1000 rpm

3. The structure and main Technical parameters of hydraulic driving experimental bench of the tool

3.1. Main structure of hydraulic driving experimental bench of the tool

Figure 4 shows the structure of hydraulic driving experimental bench for the tool. The purpose of designing the hydraulic driving experimental bench of the tool is to simulate the working condition of the scene.
1-Control cabinet (frequency conversion control, data monitoring), 2-Ladder assembly, 3-Adjustment unit of analog hole deviation angle, 4- Submersible electric pump, 5-Water recycling tank, 6-Analog turnplate unit, 7-High pressure lines (including manometer, flow-meter), 8-Reservoir, 9-Centrifugal pump with frequency conversion control, 10-automatic vertical drilling tool, 11-The pointing of analog hole deviation angle, 12- Test unit on pushing force, 13-main support.

Figure 4. General structure diagram of hydraulic driving experimental bench for the tool.

The analog turnplate unit with variable frequency motor drives the tool rotating. The adjustment unit of analog hole deviation angle tilts the tool at a certain angle. Replacing the drilling fluid with clear water, the centrifugal pump with frequency conversion control drives the clean water circulating. In order to realize the function of hole straightening and angle holding of the tool, the thrust plate of the actuator can be opened at the high side and retracted at the bottom side of the well deviation. The data monitoring and data collecting parts can collect the parameters of the system such as inlet flow, backwater flow, pressure and pushing force with hole straightening. The data test unit of experimental bench is composed of sensor module (including flow-meter, manometer, lateral force, temperature, rotational speed sensor, etc.), signal processing module, acquisition control module and power supply. The test data is sent to the computer by serial port.

3.2. Main technical parameters of experimental bench

Table 1 shows the main equipment technical parameters of the hydraulic driving experimental bench of the tool.

Table 1. Technical parameters of main equipment of hydraulic driving experimental bench for the tool.

| name                              | model      | main parameters          |
|-----------------------------------|------------|--------------------------|
| DF multistage corrosion resistant centrifugal pump | DFH155-67×8 | 43L/s, 440KW             |
| submersible pump                  | WQ(D)20-5-0.75F | 20 m³/h                 |
| water storage tank                | 2700×2400×9000 | 58 m³                  |
| Backwater tank                    | 800×1500×1000 | 1                       |
| Variable frequency motor          | Y2-112M    | Output speed satisfied that: 200 ~ 700r/min |

The main technical parameters of the experimental bench are as follows:

- Height of experimental bench: ≤5.1m
- Maximum working pressure of hydraulic pipeline of the system: 10MPa
- Speed of Analog turnplate: 0 ~ 150r/min
- Displacement of circulating water: 20 ~ 45 l/s
- Outer diameter of the tool: ø311mm
- Angle of hole deviation angle: ≤8.0°
3.3. The design of detail structure

Figure 5 shows the structure of analog turnplate unit. The analog turnplate of experimental bench has the rotating function. The analog turnplate can simulate the rotation of drilling tool and can measure and control the rotational speed of the tool in real time. It also can debug the tool's function of hole straightening and angle holding under relatively "real" drilling conditions, laying the foundation for field testing of the tool.

![Diagram of analog turnplate unit](image)

Figure 6 shows the adjusting mechanism of analog hole deviation angle. The adjusting mechanism of analog hole deviation angle can adjust the driving mechanism and the stabilized platform to a certain angle, simulating the space attitude of drilling tool. The leading screw with trapezoidal thread and the nut can quickly adjust the angle of analog hole deviation angle. Through the pointer and dial, the angle of analog hole deviation angle can be accurately read. The angle adjusting range of this device is ±8°.

The automatic vertical drilling tool rotates under the driving of the turnplate. When the hole deviation angle exceeds the set range, the high-pressure fluid passageway opens at the high edge of well. And the fluid entering through the passageway, which has pushed the thrust plate to the high edge of the well. The pushing force created by thrust plate forces the drill to cut the low side of the well, and the functional command of the hole straightening is completed. If the hole deviation angle doesn’t exceed the set range, the thrust plate will push against the borehole wall alternately, and the effect of angle holding is achieved. The purpose of hole straightening for pushing force is to overcome the influence of the formation deflecting force to borehole verticality. If the well deviation exceeds the allowable range, the pushing force will be adjusted by actuator to correct deviation in time, otherwise, the system will support the borehole wall with equal thrust to maintain the vertical state. Figure 7 shows the test unit structure on pushing force.

The tool is installed on hydraulic driving experimental bench, connecting with the data acquisition circuit. The analog turnplate device makes the tool rotate. Turning on the frequency conversion pump, regulating the frequency, and starting the test of clean water circulation. The frequency of the pump is increasing step by step. In the meantime, collecting the frequency, influent flow, the speed of turnplate and pushing force and other data. The test shows that the hydraulic driving experimental bench can establish a clear water circulation to simulate the variation of drilling fluid flow rate. It also can
simulate the variation of the turnplate speed and the well deflection, getting the test condition of the tool closer to the actual drilling condition. The experimental bench can measure the pushing force of the thrust plate in the tool. And it can obtain a suitable range of the displacement on the drilling fluid and the rotating speed on the turnplate. It also realizes the function of hole straightening and angle holding at the hole deviation angle of 1.5°.

4. Experimental requirements and technical difficulties

This experimental bench is 5.1 m high adopted the modular design. The lifting assembly is composed of an analog turnplate unit in figure 4, an automatic vertical drilling tool and a pushing force test unit. The experimental bench weights about 1800 kg, requiring the use of a crane during installation. The sealing of the pipeline should be ensured during the installation of the experimental bench.

The frequency conversion control motor with analog turntable first adopts a low speed with a frequency less than 5 Hz. Making sure it is normal by observation, hearing and other confirmation before the test. Checking the water volume in the pool, emptying the air in the centrifugal pump, trying to run the clean water circulation, checking the leakage of the loop and the pressure value of the pressure sensor. Running the rotation subsystem at low speed to ensure the revolving safety of the whole system.

The experiments what have been completed on the hydraulic driving experimental bench for the tool are as follows: the turbine parameters testing test of turbine generator what determined and optimized the turbine parameters, joint testing test of upper and lower turbine motor, the control function testing test of the stabilized platform under hydraulic driving, and the comprehensive testing test of the overall performance of the tool function. The hydraulic driving test of the tool is in accordance with the design requirements before delivery.

Technical difficulties: (1) Since the dynamic sealing of both the analog turnplate unit and the force-measuring unit, it is necessary to ensure that the water in pipeline doesn’t leak during the experiment. (2) Since the total height of the automatic vertical drilling tool and its connector part is about 4 m, and its rotation depends on the analog turnplate. So it is difficult to keep the tool rotating at a uniform speed.
5. Conclusion
The successful development of automatic vertical drilling tool with independent intellectual property rights must go through the stages of overall design, unit experiment, hydraulic driving experiment, field test and so on. The development of hydraulic driving experimental bench of tool is the most important bench. The multistage corrosion resistant centrifugal pump in clean water circulation system has been adopted in hydraulic driving experimental bench of automatic vertical drilling tool. The unit experiment and the ground comprehensive simulation experiment show that, the hydraulic driving experimental bench of the automatic vertical drilling tool developed by the author's scientific research team is reasonable in structural design, complete in function and appropriate in technical parameters, which can meet the needs of the project.

Acknowledgments
This paper obtained financial support from the special fund project of the innovative four projects construction on the enterprise technology center in Shaanxi province (the project: Development of automatic vertical drilling system, Shaanxi industry and information technology and development, (2010) No.396) and the national oils and gases drilling equipment technology research center. (Project: Development of automatic Vertical drilling tools, New 2015-16). I would like to thank my colleagues in the Institute of Petroleum Machinery of Xi’an Shiyou University for their support in the design work. And I wanted to thank the Baoji Oilfield Machinery Company’s strong support about processing, assembly, unit test and field test in the development of automatic vertical drilling tool.

References
[1] CHEN R M, LIU W, CHEN J L, et al. Field test of Ф311 mm vertical drilling system [J] 2010 Chin.J. Oil Drilling & Production Technology 32(3):4-8
[2] SUN Y N, LI S L, GE Y H, et al. The design and control ways of the downhole automatic closed loop of vertical drilling tool [J] 2001 Chin.J. Acta Petrolei Sinica 22(4):87-91
[3] RU D J, ZHANG J G, ZHOU S P, et al. Application of the vertical drilling system BVT5000 on Well Keshen 203 [J] 2012 Chin.J. Oil Drilling & Production Technology 34(4):1-3
[4] HAN L J, NI H J, ZHAO J H, et al. Development of mechanical tool for automatic vertical drilling [J] 2008 Chin.J. Acta Petrolei Sinica 29(5):766-68
[5] YAN W H, PENG Y and ZHANG S H. Mechanism of rotary steering drilling tool [J] 2005 Chin.J. Acta Petrolei Sinica 26(5):94-97
[6] YAN W H, PENG Y and SHI H X. The design of working fluid control distribution in rotary steering drilling tool [J] 2005 Chin.J. Drilling & Production Technology 28(5):69-72
[7] YAN W H, PENG Y. Design of steering executive unit of rotary steering drilling tool [J] 2006 Chin.J. Natural Gas Industry 26(11):70-72
[8] YAN W H, PENG Y, ZHANG S H, et al. Mechanical design of stabilized platform unit in the rotary steering drilling tool [J] 2006 Chin.J. Drilling & Production Technology 29(4):73-75
[9] YAN W H, PENG Y, ZHANG S H, et al. Research on Rotary Steerable Drilling System[J] 2016 Ukraine J. Metallurgical and Mining Industry (2):144-48
[10] WANG X T, WANG W T, MENG R B, et al. Design of integrative performance test rack for automatic vertical drilling tool system [J] 2017 Chin.J. China Petroleum Machinery 45(2):13-16
[11] WANG W T, WANG X T, YANG X Y, et al. Field test of full-rotation backup-type automatic vertical drilling tool [J] 2015 Chin.J. China Petroleum Machinery 43(9):24-27
[12] WANG W T, WANG J Q, WANG X T, et al. Development of full rotation and push-the-bit type automatic vertical drilling tool [J] 2015 Chin.J. China Petroleum Machinery 43(8):47-50
[13] WANG W T, WANG X T, YANG XY, et al. Performance simulation test of turbine generator for automatic vertical drilling tool [J] 2016 Chin.J. China Petroleum Machinery 44(7):12-15
[14] YAN W H, PENG Y and WU H. The Research and Development of Automatic Vertical Drilling Tool[C] 2016 International Conference on Mechatronics and Automation IEEE (Harbin, China) pp 1226-31