Comparison Study of Leading Rotary Steerable System and Future Development Trend

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Abstract—The rotary steerable system is critical drilling equipment urgently needed in the development of unconventional oil and gas fields in China. It is still a significant but unavailable technology for China's petroleum industry. With the high demand for rotary steerable system in unconventional oil and gas development, this paper studies RSS tools from major oilfield service companies. Different tools from major oilfield service companies and their technical specifications were studied. Firstly, the development history of the rotary steerable system is introduced, and the tools are then classified into different categories based on control and biasing methodologies. The key technical parameters of the RSS were compared and analyzed. Moreover, a detailed comparison of the 475, 675 and 900 series of tools has been carried out. The current development focuses of rotary steerable tools include high dogleg severity, high temperature and high pressure and integrated navigation scheme with inertial and magnetic methods. Finally, the development trends of the RSS were forecasted. The objective of this paper is to provide an overview and latest development of the rotary steerable system for developer, operation and maintenance population in the drilling industry.

1. Introduction
Oil and natural gas are strategic resources related to the national economy. China's oil and gas demand is increasing every year. The "BP World Energy Statistics Yearbook" [1] shows that China's energy consumption in 2017 had an increase of 3.1%, of which oil consumption increased by 3.6%. China's statistics point out that in 2018, China's dependence on foreign crude oil rose to 70.8%, and its dependence on natural gas rose to 43%; for the first time, China became the world's largest oil and natural gas importers at the same time, and this upward trend continued in 2019. Experts pointed out that China's energy dependence on foreign sources became too high, and this could cause energy security concerns.

Unconventional oil and gas exploration in China is very challenging. The increase in well depth will inevitably lead to the continuous improvement of technology and equipment requirement[2]. Therefore, it is imperative to use techniques such as Rotary Steerable System (RSS) and hydraulic fracturing to increase industrial production [3]. However, the core technology and equipment of RSS are mainly monopolized by large oilfield service companies such as Schlumberger, Halliburton and Baker Hughes,
occupying about 90% of the global high-end service market. Their high-end products only provide "packaged services". In order to solve these challenges in the future, the "Outline of National Innovation-Driven Development Strategy" clearly requires "development of exploration and exploitation technologies for oil and gas mineral resources under complex conditions such as deep-sea and deep ground and development of comprehensive technologies for the exploration and development of unconventional oil and gas such as shale gas."

China's existing major oilfields have a severe shortage of reserves, and conventional oil and gas production continues to decline. In contrast, China's deep oil and natural gas resources have the vast potential [4], accounting for 52% and 28% of the total geological resources, which can become future energy breakthroughs [5,6]. In recent years, oil and gas exploration and development has gradually shifted to unconventional oil and gas fields such as low permeability, deep and ultra-deep, deep ocean water, and shale oil and gas [7].

So far, China's scientific research institutions have achieved some remarkable results [8]. However, few RSS have been put into commercial services. Therefore, the RSS in the development of unconventional oil and gas fields in China depends on foreign oil service companies. Therefore, the RSS is still the essential-to-own technology of China's petroleum industry.

2. The development history of RSS
The original development purpose of the RSS was to overcome the problem of low efficiency of the motor in the directional drilling process. Many technology companies around the world began to develop technology in the 1990s. These companies formed their prototypes in the late 20th century. Around 2000, the world's three largest oilfield service companies Schlumberger, Halliburton and Baker Hughes, through a combination of independent development and commercial integration, each formed an RSS for commercial applications. Subsequently, drilling companies such as Smith, Precision and Gyrodata also introduced their RSS [9].

According to the Spears market survey, in 2019, the global directional drilling market exceeded 10.4 billion U.S. dollars. In the past ten years, the share of RSS in directional drilling applications has increased year by year. Since mid-2012, RSS has accounted for more than 50% of the directional drilling market, and this proportion has increased to more than 70% by 2019. In terms of market share, Schlumberger, Baker Hughes and Halliburton accounted for more than 50% of the global directional drilling market; among them, Schlumberger alone accounted for nearly 27% of the directional drilling market Share. Schlumberger has the most complete RSS, which can meet the drilling challenges of different formations, different build rates and different environmental requirements.

3. RSS Classification
The RSS generally includes two main parts: the control platform and the biasing mechanism. The control platform of the RSS is categorized into a stable platform and a strapdown type. The working principle of the stabilized platform is that it does not rotate with the drill string during the drilling process, and is stabilized in a fixed direction to provide steering control. The working principle of the strapdown platform is to rotate with the drill string during the drilling process and can be completed Guiding control of the biasing mechanism.

The biasing mechanism has developed three steering mechanisms: push-the-bit, point-the-bit, and hybrid.

- Push-the-bit steering mechanism: the drill bit, the lower and the upper centralizers form a three-point contact. Under the control of the control platform, the ribs extend out and interact with the formation, and through the reaction force of the formation, the bias steering function of the bit direction is realized.
- Point-the-bit steering mechanism: the drill, the lower and the upper centralizers form a three-point contact. Under the control of the control platform, the internal structure "bends" the shaft in the system, and the system main shaft is connected with the drill shaft to realize the offset guiding function.
• Hybrid steering mechanism: the drill bit, the lower and the upper centralizer form a three-point contact. The system combines the principles of push-to-bit and point-the-bit systems in order to provide the maximum tilting capacity [10].

4. Parameter analysis of RSS
For users of RSS, the focus is mainly on the technical parameters of the tool. These parameters can be classified explicitly as:
• Parameters related to steering control: maximum build rate, deviation angle and azimuth measurement distance;
• Tool environment-related parameters: maximum internal pressure, flow range, aperture range and maximum temperature;
• Related parameters of mechanical speed: maximum rotation speed and maximum WOB;

In order to facilitate the judgment of the performance differences of the RSS tools of different sizes and different steering modes, this paper collects the technical parameters of the RSS commercialized by major international oil service companies[11,12], which are divided into three types according to different sizes. Large commonly used sizes, including 475 (4.75 inches (0.121 meters)), 675 (6.75 inches (0.171 meters)) and 900 (9.00 inches (0.229 meters)) series, and are based on the same orientation model, for each model of major companies. The important parameters of the RSS tools are sorted and compared.

Figure 1 475 series RSS tool aperture and flow range comparison chart

Figure 1 compares the tool size and flow range of the 475 series.
Figure 2 compares the five important parameters of the 475 size series of RSS tools. It can be seen from the figure that the Schlumberger PowerDrive Archer 475 in the illustrated series has the largest building rate, which is 18°/100 feet (18° /30.480 meters). Among them, the Baker Hughes 475 AutoTrak eXact, which can withstand the maximum internal pressure and maximum temperature, are 30k psi (206.910 MPa) and 165 °C, respectively. For the tools shown in the series, they are more suitable for drilling operations in high temperature and high-pressure environments.
**Figure 2** Comparison chart of important parameters of 475 series RSS tools

**Figure 3** 675 size series RSS tool aperture and flow range comparison chart

Figure 3 compares the tool size and flow range of the 675 series.
Figure 4 Comparison chart of tool size and flow range of 900 size series RSS

Figure 5 675 size series RSS tool important index comparison chart

Figure 5 compares the five important parameters of the 675 size series of RSS tools. It can be seen from the figure that the Schlumberger NeoSteer CLx in the illustrated series has the largest building rate, which is 16°/100 feet (16°/ 30.480 meters).

As shown in Figure 4, comparing the tool size and flow range of the 900 series.
As shown in Figure 6, the five important parameters of the 900 size series RSS tools are compared. It can be seen from the figure that the Halliburton Geo-Pilot Dirigo RSS 9600 in the illustrated series has the largest building rate, which is 10°/100 feet (10°/30.480 meters).

As shown in Figure 7, the current types of commercial RSS tools under several major international oil service companies are organized and compared regarding its maximum building rate capability. It can be seen that Schlumberger has a complete RSS, which can meet the drilling requirements of different formations, different build-up rates and different environments, including six common sizes such as 475, 675, 825, 850, 900, and 1100. Furthermore, three steering modes and Schlumberger's PowerDrive Archer 475 and Halliburton's iCruise intelligent RSS have the largest build-up rate capability of currently known commercial RSS tools, reaching 18°/100 feet (18°/30.480 meters). Besides, The iCruise intelligent RSS is a tool commercialized by Halliburton in 2019. Its main feature is that the iCruise intelligent RSS can realize program automation in precise wellbore positioning, thereby helping operators through faster drilling speeds. Reliable performance and predictable results reduce drilling time [14].

5. Analysis of foreign research development
Since the 1990s, after more than 30 years of rapid development, foreign RSS has been continuously improved in terms of surface control, signal transmission, signal measurement, downhole control, and
RSS. At present, foreign RSS has matured in terms of geometric trajectory RSS; as the number and proportion of deep wells, ultra-deep wells, special process wells, and high-temperature and high-pressure wells gradually increase, there are still many directions for RSS that need to be broken.

5.1. **RSS with high build rate**
As shown in Figure 8, the high-build rate RSS can move from vertical to horizontal in a shorter path, thereby effectively increasing the vertical distance and increasing the contact length of the horizontal section, which can reduce drilling costs and increase subsequent production. Therefore, the RSS with high build rate has become an indispensable weapon in the process of unconventional oil and gas development, and it is also one of the current research and development directions in China. RSS with high build rate generally refers to build rates greater than 15°/100 feet (15°/30.480 meters). In the past five years, high build rate RSS has become a hot spot for development, including Schlumberger's Archer [15,16], Schlumberger's push-the-bit high-inclination on-bit RSS NeoSteer CLx [13] and the near-bit RSS CL [17], Halliburton's iCruise[14] and Baker Hughes' AutoTrak Curve [18].

![Figure 8](image)

**Figure 8** High-building rate RSS increases oil layer contact

5.2. **RSS combined with inertial and geomagnetic navigation**
In 2018, Schlumberger launched the PowerDrive Xcel tool, which has a steering mode combining inertial and geomagnetic navigation. PowerDrive Xcel belongs to the full-RSS in the PowerDrive family. PowerDrive Xcel relies on the geomagnetic and gravitational field measurement data to control the steerable system, enabling it to achieve precise direction control in an environment of substantial magnetic field interference [19,20]. The system application can be customized for extended reach wells to optimize the curvature transmission and strictly control the extended tangent area.

5.3. **Highly reliable and highly integrated RSS**
Foreign oil service companies continue to improve the reliability of the RSS through technology accumulation and design iterations. After nearly 20 years of commercial development, Schlumberger's PowerDrive X6 tool has reached a high mean time between failure (MTBF) reliability [21]. The "factory drilling" system [22], which integrates the logging while drilling and RSS, make the downhole drilling tool assembly simpler and more efficient. Therefore, foreign companies will invest more in research and development in the direction of highly integrated rotation.

5.4. **High temperature and high-pressure RSS**
With the development of electronic technology, the temperature and pressure resistance of the RSS will be further enhanced; with the increase of complex structure wells and highly difficult directional wells, more oil service companies participate in the development of new RSS technologies through joint means. In 2008, Total and Halliburton cooperated to develop sensors used in high-temperature and high-pressure resistant RSS, which have been applied in several high-temperature wells and achieved good
results. Schlumberger's PowerDrive ICE tool uses multiple chip technology (Multiple Chip Module, MCM), the operating temperature index reaches 200 °C; the withstand voltage can reach 207 MPa [23].

6. The development trend of foreign RSS
The following two aspects are expected to become the future development trend of foreign RSS.

6.1. Highly instrumented guide function integration
At present, since most of the RSS put into use do not have the geological evaluation function, the RSS is not fully mature, and can only be used in conjunction with geological evaluation instruments, using the geological parameters measured by the geological evaluation instruments for geo-steering. Now, many drilling service companies in the world are working on the research and development of RSS with geo-steering function and have made significant progress. In 2016, Schlumberger launched the EMLA (Electro-Magnetic Look-Ahead) prototype with a forward detection distance of 30m [24].

6.2. Drilling automation
At present, foreign companies that have RSS, logging while drilling tools (MWD) and logging while drilling tools (LWD) have concentrated scientific research to develop RSS with closed-loop automatic control [25]. The development of foreign RSS has become a systematic and automated trend [26]. The development of automation is based on closed-loop controlled navigation [27]. With the help of systematic development, future directional drilling will inevitably include surface and downhole systems—fully automatic trajectory close-loop control.

7. Conclusion
The research and development of RSS play an essential role in China's unconventional oil and gas development. This article analyzes different RSS by classifying and comparing their key parameters. A detailed comparison of the 475, 675 and 900 series of tools has been carried out, the recent development of RSS has been studied, and the research hotspots in the next few years have been predicted. It is hoped that this article will provide a reference for Chinese researchers in the development of rotational orientation.

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References
[1] BP. BP Energy Outlook, 2019 edition[J]. London, United Kingdom, 2019.
[2] SHI X B,YU Z C,CHEN P. Hole trajectory design and control theory for sidetracking horizontal and branch wells [M]. Beijing: Petroleum Industry Press, 2009, 1–20.
[3] CHEN P,LIU Y,MA T S. Current status and prospect of shale gas "well factory" drilling technology [J]. Petroleum Drilling Technology, 2014, 42(03): 1–7.
[4] TIAN G. Unconventional oil and gas will become an important strategic succession for conventional oil and gas [J]. Natural Gas Industry, 2019, 39(12): 123.
[5] FAN Z W. Global natural gas development pattern and analysis of China's natural gas development direction [J]. China Mining, 2018, 27(04): 11–22.
[6] ZOU C N,YANG Z,ZHU R K, et al. Progress in China's unconventional oil and gas exploration and development and theoretical technology [J]. Chinese Journal of Geology, 2015, 89(06): 979–1007.
[7] ZHANG N N, WANG Q, WANG J J, et al. Characteristics of oil and gas discoveries in recent 20 years and future exploration in the world[J].China Petroleum Exploration, 2018, 23(01): 44–53.
[8] YANG C X, WANG R H, HAN L J, et al. Development of the Strap-Down RSS and Field Test[J]. Journal of Petrochemical Universities, 2019, 32(06): 90–96.

[9] XUE Q L, DING Q S, HUANG L L. The Latest Progress and Development Trend of Rotary Steering Drilling Technology[J]. China Petroleum Machinery, 2013, 41(07): 1–6.

[10] BRYAN H H, COX J, BLACKWELL D, et al. High-Dogleg Rotary-Steerable Systems: A Step Change in Drilling Process[C]//Society of Petroleum Engineers, 2009.

[11] 2019 RSSs Directory[J]. Offshore, DRILLING & COMPLETION, 2019.

[12] 2017 RSSs Directory[J]. Offshore, DRILLING & COMPLETION, 2017: 38–42.

[13] NeoSteer CLx Extreme Curve and Lateral At-Bit Steerable System | Schlumberger[EB/OL]. [2020-02-26]. https://www.slb.com/drilling/bottomhole-assemblies/directional-drilling/neosteer-at-bit-steerable-systems/neosteer-clx-rotary-steerable-system.

[14] ZALLUHOGLU U, TILLEY J, ZHANG W, et al. Downhole Attitude-Hold Controller Leads to Automatic Steering of Directional Wells with Improved Accuracy and Reduced Tortuosity[C]//Society of Petroleum Engineers, 2020.

[15] TIPU I, ALAWADHI E, KUMAR R, et al. Bending Rules with High Build Rate RSS[C]//Society of Petroleum Engineers, 2015.

[16] ALBARDISI T, AKMETOV R, SANDERSON M, et al. Hybrid High Build Rate RSS Improves Challenging Directional Control in a Soft Abrasive Drilling Environment in Oman Drilling Operation[C]//Society of Petroleum Engineers, 2014.

[17] NeoSteer CL Curve and Lateral At-Bit Steerable System | Schlumberger[EB/OL]. [2020-02-26]. https://www.slb.com/drilling/bottomhole-assemblies/directional-drilling/neosteer-at-bit-steerable-systems/neosteer-cl-rotary-steerable-system.

[18] KHATTAB H M, ISMAIL A I, ABDALLA M E, et al. High Build Up Rate RSS Leads to Revolutionize Onshore Horizontal Drilling in Western Desert of Egypt[C]//Society of Petroleum Engineers, 2016.

[19] HUSSAIN S, LI F, RANA V, et al. New Inertial Steering Mode of Point-the-Bit RSS Expands Tool Operational Envelope[C]//International Petroleum Technology Conference, 2016.

[20] LI F, BALKA M, AL-GHAZZAWI A. Successful Application of a New Inertial Steering Mode of Point-the-Bit RSS in Middle East Oilfield[C]//Society of Petroleum Engineers, 2017.

[21] WAND P A, BIBLE M, SILVESTER I. Risk-Based Reliability Engineering Enables Improved Rotary-Steerable-System Performance and Defines New Industry Performance Metric[C]//Society of Petroleum Engineers, 2006.

[22] HUMMES O, BOND P R, SYMONS W, et al. Using Advanced Drilling Technology to Enable Well Factory Concept in the Marcellus Shale[C]//Society of Petroleum Engineers, 2012.

[23] PowerDrive ICE UltraHT RSS | Schlumberger[EB/OL]. [2020-03-11]. https://www.slb.com/drilling/bottomhole-assemblies/directional-drilling/powerdrive-ice-ht-rotary-steerable-system.

[24] CONSTABLE M V, ANTONSEN F, STALHEIM S O, et al. Looking Ahead of the Bit While Drilling: From Vision to Reality[J]. Petrophysics, Society of Petrophysicists and Well-Log Analysts, 2016, 57(05): 426–446.

[25] ZALLUHOGLU U, DEMIRER N, MARCK J, et al. Steering Advisory System for RSSs[C]//Society of Petroleum Engineers, 2019.

[26] HANSEN C, STOKES M, MIETING R, et al. Automated Trajectory Drilling for RSSs[C]//Society of Petroleum Engineers, 2020.

[27] MATHEUS J, IGNOVA M, HORNBLOWER P. A Hybrid Approach to Closed-Loop Directional Drilling Control Using RSSs[C]//Society of Petroleum Engineers, 2014.