WORLD’S FIRST HIGH CURVATURE ROTARY STEERABLE SYSTEM

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ABSTRACT
Rotary steerable systems (RSS) have been in the market for more than a decade and their advantages in delivering smooth well bores and cost savings due to performance improvements have been well established.

Today's RSS are however limited in the maximum dogleg severity that they can deliver compared to the conventional positive displacement motors (PDM). For example in the 8.5in section the maximum dogleg quoted by major service companies are in the range of six to eight degree per hundred feet. Any well planned above this dog leg range in this hole section is drilled by PDM.

A new rotary steerable drilling tool capable of delivering reliable and consistent doglegs in the range of 0 -15 deg/100ft in any type of formation has been developed. Higher curvature rates imply that kick-off-points can be pushed deeper, which helps improve ROP due to longer vertical section drilled. Additionally at high curvature rates, horizontal displacement needed to land the well is dramatically reduced (380ft at 15deg DLS compared to 1145ft at 5deg DLS). This helps in early entry into reservoir and higher production rates.

In addition to these capabilities, the system can also kick-off from vertical, perform open-hole sidetracks, execute closed loop trajectory controls. All these capabilities enable the drilling of even more complex well profiles in one run without the need to trip out of hole, resulting in significant performance improvements, time and cost savings.

In this paper we will discuss the principle of operation of the high dogleg RSS and we will also present results from various field tests validating the applications of the tool.

INTRODUCTION
Fully rotating RSS are far superior, in overall well delivery, to positive displacement motors and RSS that have non rotating sections. Some of the key benefits of such systems are:

- Eliminates slide rotate profiles, resulting in smooth well bore
- Continuous rotation of all components of the drill string, resulting in better hole cleaning
- Delivers Good Quality well bore, enabling ease of casing runs and better logging data quality

All the above ensures a overall increase in ROP resulting in time and cost savings

However, dog leg severity capability of the rotary steerable systems available on the market today is formation and borehole dependent. In case of extremely soft formation and/or borehole washouts the max DLS decreases, resulting in trip out of hole to pick up motors. This adds additional cost and time to the AFE. An innovative RSS was developed in order to overcome these issues.
PRINCIPLE OF OPERATION

Traditionally, all RSS are divided into Push or Point the Bit systems. Push the Bit systems are generally simple and involve a mechanical device that pushes against the borehole wall misaligning the axis of the tool to the borehole axis to deliver the force at the bit to deviate the wellbore in the desired direction. Due to this, Push the Bit systems are very much affected by the environment, such as formation type and borehole profile. Point the Bit systems are complex mechanically, with an internal “bend” in the tool causing the misalignment of tool and borehole axis which results in the directional response. Due to the internal nature of the bend, these are less prone to the environmental effects.

The new High Dog Leg RSS (Figure 1) is a hybrid system that combines the best features of Push and Point the Bit systems and is capable of delivering consistent and reliable high DLS in soft or hard formations. In order to maximize the RSS benefit, all components of this system rotate fully with the drill string. In steering mode, the electronics stabilize a geostationary valve that diverts small portions of the mud to the pistons internal to the Steering unit. When energized, the pistons strike against the inner diameter (ID) of the steering sleeve. The amount of deflection of the steering sleeve is limited mechanically and electronically. The sleeve is hinged on a universal joint which acts as a pivot point and points the bit in the desired direction. In neutral mode, electronics rotate the valve continuously, and the bit force is uniformly distributed along the borehole wall, as well as along with borehole axis.

![Figure 1: Sketch of High Dog Leg RSS](image)

ENGINEERING TEST WELL

As with all product development in Schlumberger, extensive tests were carried out in engineering centres to qualify this new High Dog Leg RSS. Once the mechanical integrity for downhole use was verified, the tool was tested for its directional drilling capabilities in the Schlumberger Drilling Rig Testing facility in Cameron, Texas. Rig capabilities: 900HP drawworks (410Klbs pull limit), 900HP 271/2in rotary, 136ft triple with 750Klbs static hook-load capacity, 1700HP mud pumps (2x 1000GPM at 2500psi), 13-5/8in 5000psi double ram BOP. Shown below are some pictures of the rig.

![Figure 2: Section View of Test well](image)  ![Figure 3: Plane View of Test well](image)
Figures 2 & 3 above show the well profile of the test well drilled in the test facility. Figures 4 and 5 below summarize the results of drilling main and sidetrack holes. Shown in the graphs are trend of Inclination, Azimuth, Dog leg severity, Surface weight on bit (SWOB), along with the type of formations drilled, shale (dotted yellow) and sand (dashed blue).

The main hole drilling (shown in blue curve) started off with a vertical hold followed by a kick off at shallow depths, Closed loop Inclination hold trajectory testing, and finally the tool was tested for its response at various Tool Face settings in Quadrant 1 and 2, there by changing the well bore azimuth by almost 90 deg. Once this was complete, a wireline log was run to TD without issues callipering the well bore.

Then, the most challenging spot for an open hole sidetrack was picked on the main well bore – i.e. the tangent section with no DLS change. Once sidetracked ( max 4 deg DLS), the tool was tested for its linearity in dog leg at various tool face settings in quadrants 3 and 4 and while doing so the well path was turned by 180deg. Then the well was drilled near to horizontal prior to calling TD.

![Figure 4: Results from Main well bore](image1)

![Figure 5: Results from Sidetracked well bore](image2)

![Figure 6: Plot of Continuous, Stationary Surveys and DLS for Side track well.](image3)
Following are the observations and conclusions after drilling the test well:

1. The system can kick off accurately form vertical
2. High DLS can be delivered, even in soft formations which can hardly hold any weight (0.5 – 2Klbs)
3. Closed loop Inclination hold can be executed with accuracy of +/-0.5deg
4. Consistent DLS to a minimum of 15deg /100ft DLS can be achieved with high or low WOB, or in sand or shale in any TF setting
5. Controlled open hole sidetrack, even in the most challenging places in the well bore without creating excessive DLS
6. Electric logs were run on wire on the main well bore, even with 90 deg turn in the azimuth to TD without Issues, indicating a smooth borehole profile. This can be seen from the plot of Stationary and continuous surveys in Figure 6.

Based on the conclusions it was deemed that the tool is ready for use in Field tests.

FIELD TEST WELLS

Overview
The first application of the High Dog Leg (high curvature) RSS was for Southwestern Energy Corporation (SEECO) in the Fayetteville Shale play in the Desoto field. The target formation is Fayetteville shale. It is an unconventional gas reservoir located on the Arkansas side of the Arkoma Basin, ranging in thickness from 50 to 550 feet and ranging in depth from 1,500 to 6,500 feet. The shale is a Mississippian-age shale that is the geologic equivalent of the Caney Shale found on the Oklahoma side of the Arkoma Basin and the Barnett Shale found in north Texas. Refer to Figure 7 for details of location and stratigraphic column.

As of last year SEECO had drilled and completed a total of 722 wells in the Fayetteville Shale play, of which 652 were horizontal wells. Very positive results on production rates have been seen from extending horizontal lateral lengths and using closer perforation cluster spacing in completions, based on initial production rates on wells that were completed recently.

Drilling Challenges
Typically, a well is spud and air drilled to kick off point with spud rig. The kick off point is normally in the morrowon shale below the abrasive basal hale (channel sand). Dog leg requirements are usually in the range of 10 deg /100ft and a positive displacement motor is used.

Key drilling challenges faced are:
- Poor hole cleaning and stuck pipe incidences due to:
- Long slide intervals required to get 10 deg /100ft
- Lower RPMs used with large bend motors (1.83/ 2.12 )
- Drop in build rates in the transition zone in upper Fayetteville up to 30% due to formation effects

The High Dog Leg RSS was deployed to specifically address these challenges.
Prejob Phase

As a first step in the introduction of any new service or technology, a hazard identification and remedial plan (HARC) exercise was carried out to consider all the aspects of the service delivery. This included safety, training, repair and maintenance, engineering support, communication and chain of command, prejob planning, on job work flow, post job deliverables and close out. Mitigation measures were put in place for all potential hazards.

Push the Bit systems generally require an aggressive side cutting bit for delivering doglegs, whilst the Point the Bit systems need more stabilization from the bit in the form of a passive long side gauge bit. Since the High Dog Leg RSS is a hybrid, the bit selection was challenging, an extensive bit engineering work was carried out to match the bit profile to this new system.

The next important step is to ensure that the BHA is designed with correct stabilization. This was done using in house drilling simulation software. FEA modelling of the entire BHA was carried out to ensure that the integrity of the connections and collars are maintained during drilling. Figure 8 shows the typical BHA used to drill the actual well.

Hydraulics sensitivity was run with various mud weight and flow rates to ensure that the maximum stand pipe pressure is not exceeded. Pre-spud meetings were conducted at well site and in the operator’s office. BHA was pre-torqued in the base to minimize BHA make up time.
MWD STAB FLEX FLOAT High Dog leg RSS Bit

Figure 8: Typical High Dog Leg RSS BHA

Execution Phase

Well 1

The main aims of the first well were to test the tool ability to Kick off from vertical in controlled manner, deliver the curve at 10deg/100 ft or higher DLS and land the well on target TVD.

The pre-made BHA was picked up and shallow hole tested prior to running in hole. After reaming the last joint to bottom the well was successfully kicked off from vertical at 80% power setting. Streaks of basal hale were encountered, slowing the ROP drastically from 60 ft/hr to 3 to 5ft /hr. Tool continued to deliver 13 to 14deg /100ft DLS at this power setting.

Though this was greater than the planned DLS, it was decided to get ahead of the curve in case the Lower Morrowan/Upper Fayetteville shale interface affected the system (20-30% reduction in DLS) similar to that of conventional PDM assemblies. It was also decided to do azimuth corrections, if any, in the lower part of the upper Fayetteville shale.

As drilling continued through this formation, it was noted that there was a reduction in the DLS from 13 deg to about 11 deg in upper Fayetteville at 80% setting. However, once this interval was passed, the tool delivered 13 to 14deg DLS at 60% power setting. Azimuth was corrected once the well bore reached lower Fayetteville. As the well approached the horizontal entry point, the power setting was reduced to lower the DLS and enable smooth landing of the well bore. The well was landed successfully at the 0.47ft from the Target TVD and the BHA was tripped out of hole. On surface the tool passed the post run tests and it was laid down for inspection and redress. Once the lateral was drilled, casing was run to bottom without any issues. All the test objectives were fulfilled.

Figure 9 below, summarises the well graphically and Figure 10 shows the plane and section views of planned and drilled well profiles.
Well 2

The main objective on the second well was to test the repeatability of the vertical kick off, DLS capability and tool response in a lateral section. As with well 1, High Dog Leg (high curvature) RSS kicked off from vertical, drilled the curve at a max DLS of 14.84 deg /100ft. While drilling ahead and due to geological reasons, the landing point TVD was shifted deeper than planned. The well was successfully landed at the revised TVD and a 1000ft of lateral was drilled at near horizontal inclinations.

Figure 11 shows the stick slip and the DLS output from the high dogleg RSS in well 2. It is important to note that even in the presence of high stick slip and shock conditions the DLS capability of the tool was not compromised. Figure 12 shows the plane and section view of the second field test well.
Well bore quality

Figure 13 shows the plot of the continuous and stationary inclination from the high dogleg RSS run. Figure 14 shows the plot of continuous and stationary inclination from an offset well drilled in the same field, with the same rig with a positive displacement motor. Scales on both the graphs have been matched for like for like comparison.

It is clear from the graphs that positive displacement motors create a step profile in the well Bore while changing from slide to rotary mode. High DLS RSS delivers a smooth well profile even at high curvature rates.

CONCLUSIONS

Based on the results from the test well and the field trial wells, we conclude that the fully rotating High Dog Leg rotary steerable system has proven its capability to:

- Kick off accurately from vertical
- Deliver dog legs of up to 15deg /100ft in soft, hard or inter bedded formations, and under high stick slip conditions
- Precisely land the horizontal wells
- Perform open hole sidetrack, with good control over DLS
- Deliver a good quality wellbore

The directional drilling versatility of this system will enable the drillers to realize their dream of drilling complex well bore trajectories in one run.

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