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Downhole Optimization Sub Consistently Maximizes Efficiency and Minimizes Risk in Both Drilling and Well Intervention Operations

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Abstract

As the industry pushes into 3-D well profiles, extended-reach wellbores and brownfield development intervention costs continue to rise. The cost increases and potential for cost overruns are evident in all facets of drilling and well intervention operations. Technical and economic challenges faced by the industry make it absolutely critical to flawlessly execute planned operations . This paper presents case histories where a downhole optimization sub (DHOS) is utilized while drilling and also in well intervention operations to drive real-time decision making and effectively deliver answers to critical questions. The DHOS, optimization process and real-time decision making contributed directly to the operational success and reduced the risk of incurring non-productive time (NPT) events.

The following applications/well operations are being discussed in this paper:

1) Utilization in fishing operations where weight transfer is a concern. The DHOS enables the operator to perform delicate operations inside small liner/casing with a tapered string. This sub enables controlled milling operations to increase the life of the mills, shoes and small mud motor during the fishing operations.
2) When used in wellbore interventions such as pulling operations, the DHOS can also be used to reduce NPT by ensuring certain objects are properly engaged. The DHOS provides the operator critical data as to whether or not a fish is engaged prior to pulling out of the hole.
3) Milling the whipstock's window and estimating the dogleg severity for window quality indicator.
4) Real-time detection of hole spiraling due to excess steering force, formation change or wrong bit selection with implemented solutions.
5) Real-time detection of reamer dysfunctions while drilling by utilization of DHOS-specific mechanical energy.

The paper will outline case studies from various applications while drilling along with applications during well intervention where downhole electronics are rarely utilized.

In summary, these applications emphasize the use of downhole technology and real-time decision making to increase efficiency, minimize risk, and reduce NPT in well operations while drilling and in well intervention activities.

Introduction

The DHOS is designed to provide real-time optimization services while drilling and well intervention. The primary objective is to obtain downhole parameters and dynamics real time and adjust the surface parameters to optimize drilling and well intervention operations. Its continuous feedback cycle is to make the best decision with accurate downhole parameters and dynamics (**Fig. 1**).

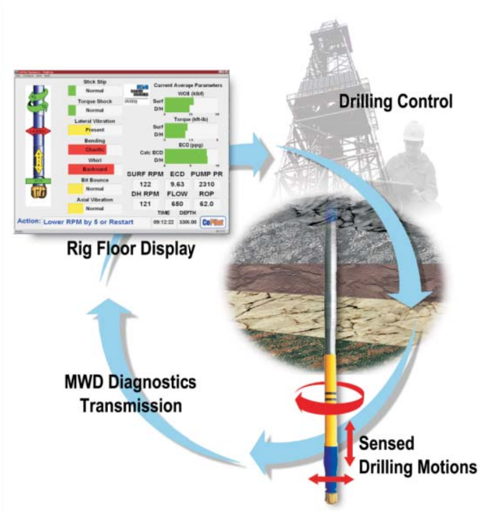

Fig. 1: DHOS continuous feedback cycle

DHOS Configuration and Measurements

The DHOS comprises the following: magnetometers, accelerometers, an axial strain gauge (WOB gauge), bending moment gauge, torsional gauge (TOB gauge), annular pressure gauge, and temperature sensor and borehole pressure gauge (**Fig. 2**).

Using the above sensors, the DHOS provides five static measurements (downhole WOB, downhole torque, RPM and motor RPM, bending moment / bending tool face, annulus and bore pressure) and four diagnostics (whirl motion, stick/slip motion, bit bounce motion and vibration, i.e., axial, tangential and lateral).

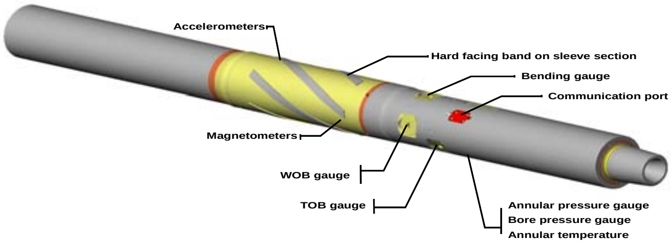

Fig. 2: DHOS configuration with different sensors

In any well intervention operation such as fishing, the surface parameters are insufficient to dictate whether the landing string is engaged with the fish before pulling out of the hole. To make a definite decision, more precise downhole parameters such as DH WOB and DH TORQUE are proved to beneficial in eliminating any NPT.

Similarly, in well intervention operations such as milling a whipstock's window, more control on downhole WOB and downhole TOB is significant to ensure that the mills are not engaged prematurely to avoid exiting the casing earlier than planned. Monitoring the downhole WOB and TOB real time from the DHOS and controlling parameters on the surface may deliver a cleaner window.

Any BHA in a curved wellbore experiences bending loads due to side forces. These side forces may be caused by gravity, wall contacts or dynamic effects in the curvature of the wellbore. Heisig et al[1] demonstrated the estimation of continuous curvature based on real-time bending moment measurements from the DHOS. Also, Hood et al[2] demonstrated how real-time bending information can successfully reduce the risk when drilling hard interbedded formations with an increased tendency to develop high local doglegs at the formation interfaces. In addition, when drilling a spiral hole due to formation changes or to the bit's gauge length, this spiral pattern can be easily detected by cyclic patterns in bending moments from the DHOS.

This paper specifically emphasizes three downhole measurements from the DHOS: bending moments, downhole WOB and downhole torque within their applications and associated case histories.

Measurements at the DHOS

Bending Loads Measurement

A bending load is also called a bending moment. An object can be modeled as shown in the diagram below, and the moments along its length can be calculated using the formula:

Bending moment = Force x Perpendicular distance

The magnitude of the bending moment varies along the length of the object. Thus, the further a section of the object is away from the load, the stronger it must be. The DHOS measures the bending strain caused by stress using the bending strain gauge as follows:

$$\varepsilon_{bx} = (M_{bx} / EI)\ y$$

where:

ε_{bx} = Bending strain
EI = Stiffness
Y = Lateral distance from the centroid
M_{bx} = Bending moments

Downhole Weight on Bit Measurements

Axial force in the BHA is determined by hook load, a buoyancy factor, drillstring/BHA weight, borehole geometry, mud weight, drag forces and the dynamics effects. The downhole WOB strain gauge bridge **(Fig. 2)** picks up axial strain (i.e., change in length within the tool), which is caused by axial force (WOB); bending moments, which are compensated for by bridge design; pressure effects, which are compensated by a pressure compensation procedure; temperature effects, which are compensated by a temperature compensation procedure; and the temperature gradient across the tool wall. Buoyancy (mud weight) and temperature effects can also be addressed via downhole tare of the sub. The DHOS measures the downhole WOB using the axial strain gauge as follows:

$$\varepsilon_N = (Ny / EA)$$

where:

ε_N = Axial strain
N = Axial force
Y = Distance from the bit
E = Young modulus

A = Cross sectional area

Downhole Torque on Bit Measurements

The torsional moment in the drillstring/BHA is determined by downhole torque, which is a function of WOB, bit aggressiveness and formation type. Downhole torque due to its close position to the bit equates to the bit's cutting torque and thus only measures torque below the tool. The DHOS uses the shear strain gauge to estimate the torsional moment or downhole torque as follows:

$$\gamma = (M_t/GI_p)\ r$$

where:

γ = Shear strain
M_t = Torsional moment or torque
G = Shear modulus
I_p = Polar moment of inertia
R = Distance for the center

Case Histories

Well 1

In Gulf of Mexico (GoM) in water depths of 3200 ft, the intent of this operation was to minimize NPT risks associated with fishing a gravel pack packer and seals in a deep (21,456 MD) and highly deviated well (75° inc). Taking into account the light weight fish, extreme depth and deviation of the well, and the need for precise control of downhole parameters, it was decided to utilize DHOS. The operation used DHOS combined with conventional fishing tools to retrieve a gravel pack seal assembly (488 lbs) and gravel pack packer assembly (5,000 lb). DHOS was also used in conjunction with a 2⅛-in. mud motor to carefully monitor downhole weight on bit, torque, and differential pressure while milling up some unexpectedly hard fill inside the gravel pack assembly. Running the DHOS tool enabled the accurate measurement of downhole weight changes, torque, and differential pressure that are impossible to see at surface.

The primary objective for DHOS on this job was to monitor weight on bit, reactive torque, and differential pressure while running a 2⅛-in. mud motor to clean fill inside the gravel pack (**Fig. 3**). Because of the extreme depth and deviation of this well, and taking into account the sensitivity of the mud motor, this operation would not have been successful without the ability to precisely monitor downhole parameters. Maximum weight on bit for the mud motor was only 3,375 lbs, and set down weight could not be seen on surface until 50,000 lbs was set down on bottom.

Secondly, DHOS was used to successfully retrieve the seal assembly inside the gravel pack packer. By using the real-time weight on bit and torque data provided by the DHOS tool (**Fig. 4**), the fishing supervisor was able to successfully screw a small acme thread on the retrieving tool into the seal assembly at 20,971 feet MD. After screwing into the seals, DHOS was then utilized to jar the seals free by monitoring over pull so as not to exceed the limitations of the jars. After the jarring the seals free, DHOS was again utilized to verify the light 488 lbs fish weight before pulling out of the hole.

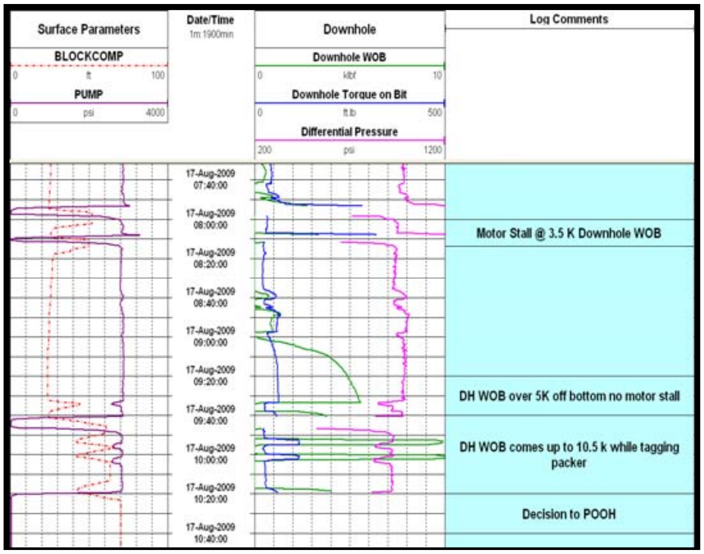

Fig. 3: Real time DH parameters during 2 1/8" motor run with DHOS

In addition, DHOS was also used to successfully retrieve the gravel pack packer assembly. This operation took advantage of the DHOS weight on bit measurements while latching into the packer to observe shearing inside the retrieving tool that would be difficult to see on surface readings alone. For this operation, the DHOS weight on bit readings were of critical importance when jarring on the packer became necessary. Initial jarring attempts at 90k over pull on surface (60k DHOS reading on bottom) proved to be unsuccessful. Maximum jarring would be required, but surface overpull was getting close to the rig's maximum capability with its current line configuration. Stringing up the block to more lines would have wasted valuable time, but DHOS verified that by pulling at the rig's maximum with 145k overpull on surface, the jars were seeing their max of 100k over pull on bottom. The rig did not have to string up to more lines, and the packer came free after only four more hits (Fig. 4). Finally, DHOS verified the packer weight as a positive indication of retrieval before pulling out of the hole.

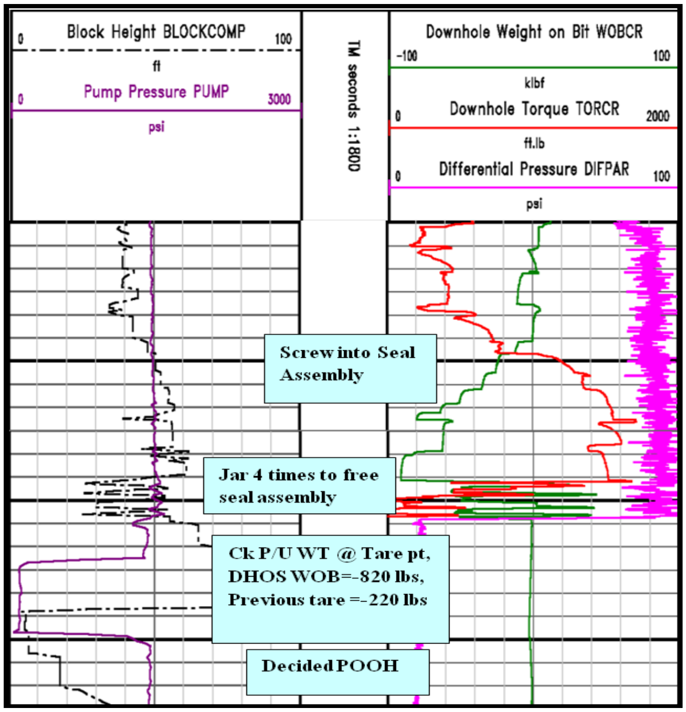

Fig. 4: DHOS verifying the packer weight before POOH

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Well 2

GoM operator using a 4½-in.. CTM-43 work string needed real-time data while fishing a bridge plug at ~17,200 ft measured depth (MD). The water depth was 1,514 ft and the packer depth was at 17,353 ft. After three unsuccessful runs the operator decided to have DHOS in the fishing assembly.

During the intervention operations, DHOS – with 14 well intervention process sensors simultaneously sampling in a dedicated sub – provided real-time data that highlighted a weight transfer issue commonly faced during fishing and milling operations. DHOS provided readings that were converted to provide weight downhole, downhole torque, annular and bore pressure, and tensile tension force.

Weight transfer is a common issue with the severity varying in each well. In addition, when fishing from a floating structure (this job was a floating semi-submersible rig), the heave compensators that try to counteract the ocean waves can introduce more error into the surface gauges that are supposed to measure the forces applied downhole. Downhole readings from the DHOS tool showed at times a discrepancy of up to 7,000 lb of compression force between the surface indicators and the DHOS downhole measurements. Surface indications fluctuated due to the rigs active compensation, and did not reflect the true force being applied to the retrievable bridge plug downhole. The fishing assembly included the DHOS downhole sensor sub combined with a 3⅛-in. grapple and Itco spear. After tagging on packer the average tension was 1,224 lb due to additional weight and drag due to packer.

It was decided to set down some weight to verify that the packer is engaged. DHOS verified the set down weight was 7,862 lb. After picking for 20 ft another set down weight was applied to confirm the packer engagement and was confirmed 8,331 lb by DHOS (Fig. 5) .After these confirmations of packer engagement it was decided to POOH and start planning the next operation eliminating NPT.

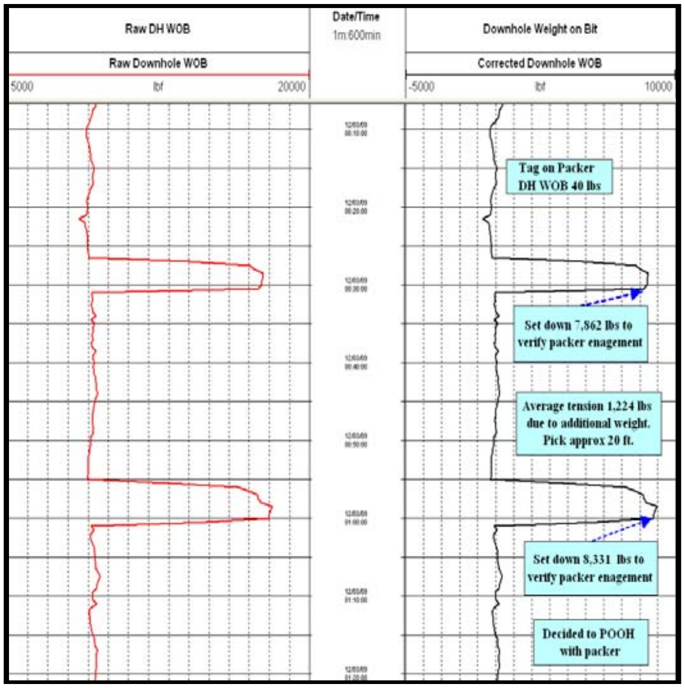


Fig 5: Downhole weight on bit from DHOS confirmed the tagging and the set down weights on packer

Well 3

Well intervention is a time- and cost-intensive operation. The most important aspect of whipstock operation is milling a clean window. The well presented in this case history was drilled in deepwater GOM, where the offset sidetrack wells had experienced high dogleg severity (DLS) while exiting the whipstock windows. These doglegs proved to be hot spots and, in several cases, cost the operator additional milling runs to obtain a clean window. Previously, the operator tried to estimate the DLS by dropping a gyro in the milling assembly but never obtained a good estimate of the local dogleg at the window. The operator decided to use the DHOS to estimate DLS using real-time bending moment data. The main objective was to mill a clean window and estimate the local DLS to eliminate any extra milling runs. A detailed procedure for milling the window was also prepared, including downhole parameters such as TOB and WOB. To estimate the DLS from bending moment data as demonstrated Heisig et al[1], a detailed simulation was performed using the service company's software to generate a DLS vs. bending moment chart for that particular milling assembly and hole geometry (**Fig. 6**). While milling the window, close monitoring was conducted for downhole WOB and downhole torque to ensure the mills were not engaged prematurely and surface parameters were adjusted to optimize the window milling. The DLS estimate, based on real-time bending moment data from the DHOS, indicated a window with a 10.5° DLS compared to a theoretical DLS of 9.89°. This estimated DLS indicated that no more milling runs were required and the mills exited the casing as planned (**Fig. 7**). No additional milling runs were performed to dress the window, eliminating undesirable NPT.

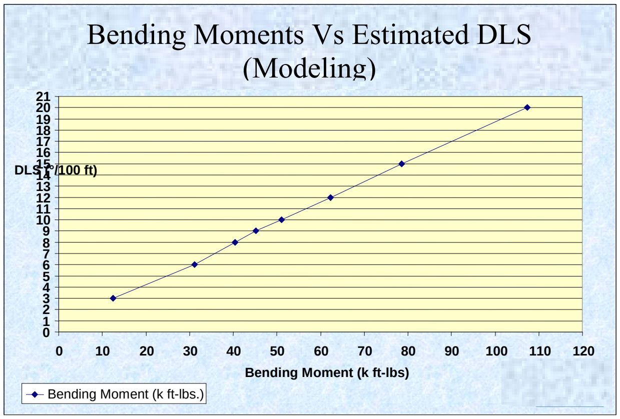


Fig. 6: Estimated DLS severity vs. bending moments for the milling assembly

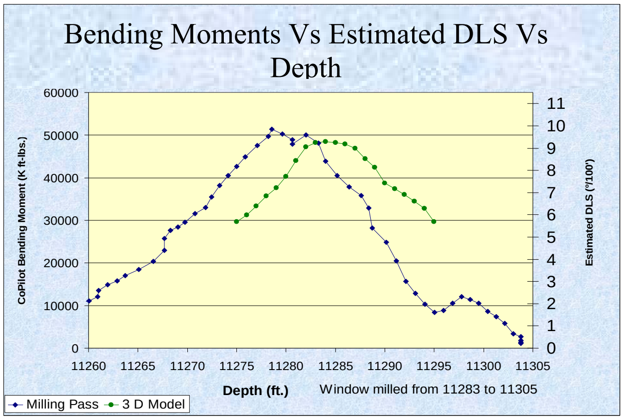


Fig. 7: Conversion of real-time BM in DLS severity over the whipstock window

Well 4

This well was planned to drill the 12¼-in. X 14¾-in. hole section using the rotary steerable assembly (RSS) with the DHOS and reamer assembly from 8,251 ft MD to 12,664 ft MD while building from 3.49° to 98.85° and turning to the right from 13.03 ° to 31.82 ° azimuth. The primary objective was to drill through the interbedded hard formations while achieving an ROP of 120 to 130 ft/hr and controlling vibration. The primary reason to use the DHOS in this hole section was to ensure appropriate WOB transfer in the curve section and, as this was reamer application, the DHOS was placed in the pilot hole just above the steerable unit. While drilling this section, a typical cyclic pattern was seen with variation of 3Kft-lb every 3 to 5 ft. This distance is equal to the distance between the bit and the steering unit, which acts as a near-bit stabilizer.

The cyclic pattern disappeared without changing any surface parameters. The same pattern was observed again at 10,662 ft MD, but this time the amplitude varied from 4Kft-lb to 5 Kft-lb accompanied with a sudden increase in surface torque and stick/slip. To break this spiraling pattern, it was decided to pick up the stand and ream through the last stand. Tripping back in the hole, it was decided to reduce the WOB and increase the RPM to eliminate stick/slip. After these procedures, the cyclic pattern disappeared with a reduction in surface torque (**Fig. 8**).

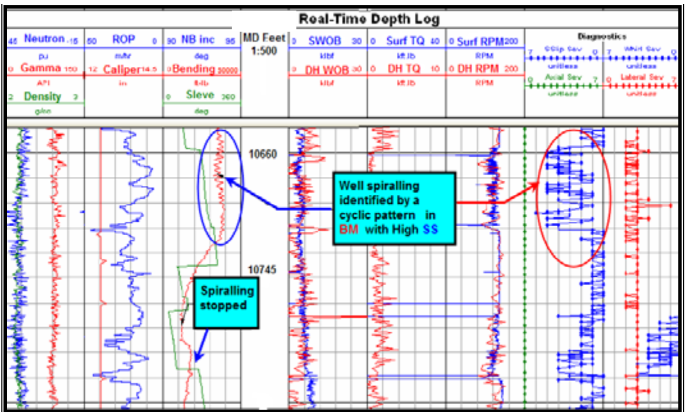
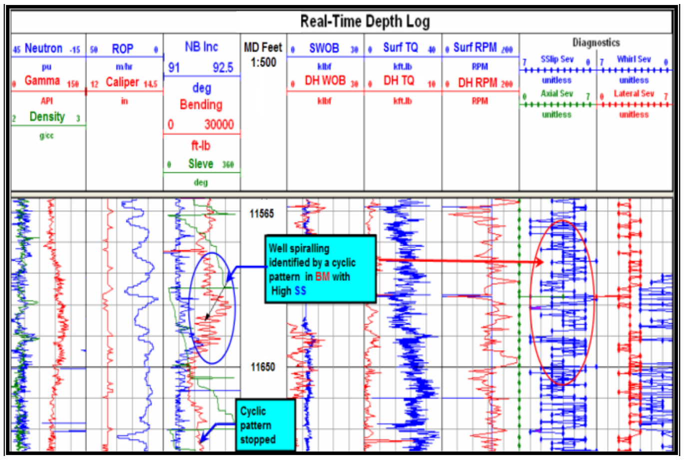


Fig. 8: Indicating bending moments cyclic pattern, a sign of hole spiraling

After drilling ahead to 11,614 ft, the bending moment cyclic pattern appeared again with an increase in surface torque and stick/slip severity. These time, bending moment values were oscillating heavily from 4 to 8 Kft-lb (**Fig. 9**). To stop this spiraling pattern, it was decided to pick off bottom as previously done and ream the last stand. After tripping back down, the same adjustments on WOB and RPM were made to eliminate stick/slip. This time, to prevent the spiraling pattern from occurring, the steering force on the RSS was reduced to a level so as to not compromise the directional plan. No spiraling pattern resulted while drilling the rest of the hole section. The section was TD as planned with an ROP of 130 to 135 ft/hr without deviation from the plan. The casing was run to the target depth without much drag as planned.



Well spiralling identified by a cyclic pattern in BM with High SS

Cyclic pattern stopped

Fig. 9: Indicating bending moments high cyclic pattern, a sign of hole spiraling

To avoid this spiraling pattern in deeper sections and future wells, the operator decided on the recommendation to use a longer gauge bit with 4 in. of gauge. The DHOS' real-time bending moment data helped to identify the hole spiraling real time, which enabled the operator to take necessary action required to eliminate undesirable events without compromising drilling efficiency.

Well 5

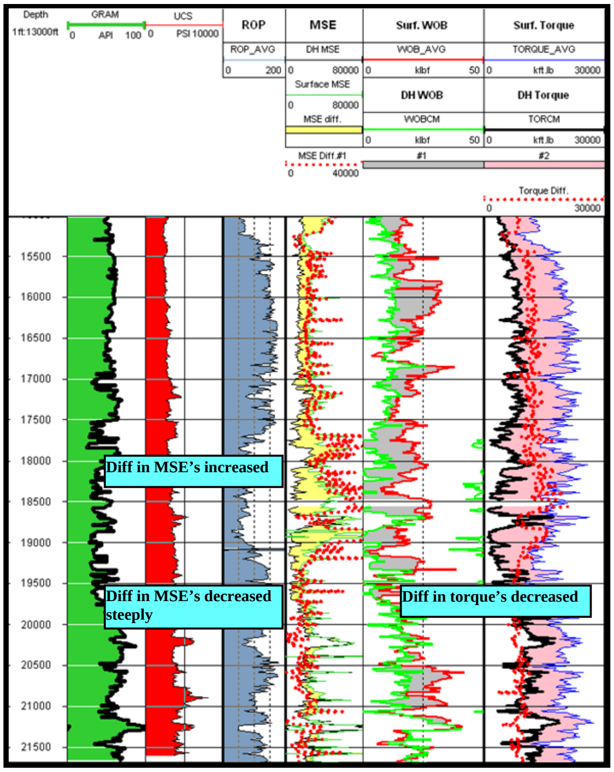
The objective of this well was to drill and underream vertically from 14,500 ft to the KOP at 16,800 ft, then keep an 6-degree tangent to 20.500 ft. Stick/slip level was high throughout the vertical section and forward whirl was constant despite of drilling parameters changes. After the buildup section was initiated stick/slip level was greatly reduced and so was the whirl level. The section TD was reached, and at that point it was believed that the operation was a success.

With the BHA at surface it was realized that the underreamer had no cutting structure left and a caliper log confirmed that the hole was under gauge from around 18,200 ft to bottom.

The traditional and conventional way to detect the reamer dysfunction real time is by monitoring the separation in SWOB and DHWOB. Apparently, the separation did not narrow much to be noticeable due to drilling dynamics, and the premature reamer failure was not detected real time, costing additional reaming runs for the operator.

To implement a new way to find reamer dysfunction a post-well analysis was conducted. After analyzing the DHOS memory data it was possible to identify when the reamer lost its cutting structure. Based on the Downhole Mechanical Specific Energy (DH MSE) and Surface Mechanical Specific Energy (S MSE) trend it was apparently cleared where the reamer failed.

The post-well analysis indicated that at around 17,400 ft the difference between the surface and the downhole MSE changed with a drastic increase in the surface MSE that remained high and erratic until approximately 18,700 ft **(Fig. 10)**. At the same time there was a slight shift in the difference between the surface and downhole torque that became steeper up to around 18,750 ft, indicating that the surface torque had an increase over the DH torque. That could have been a clue that the reamer was drilling inefficiently and that the cutters were damaged and worn out.



Diff in MSE's increased

Diff in MSE's decreased steeply

Diff in torque's decreased

Fig. 10: Differences in MSE's and torque's from DHOS dictating reamer dysfunction

There was another shift in trends from around 18,700 ft until 19,300 ft. The differences in the MSE's and torques showed a decreasing trend, indicating that the surface values were getting lower relative to the DH values **(Fig. 10).** At the same time the built-up section had started and forward whirl levels decreased and so did the stick slip. From 19,300 ft up to the section TD the surface and downhole MSE values were closer together and the same happened with WOB and torque values. This process of comparing MSE would be implemented in any future well with reamer applications to monitor reamer dysfunctions.

Conclusions

Today's downhole technologies are able to provide that much needed real-time data to make informed decisions while drilling and well intervention operations. Just a small, initial investment leads to a value proposition during the course of drilling and well intervention operations.

The authors have clearly demonstrated the use and importance of downhole optimization sub (DHOS) in drilling and well intervention operations. The case studies discussed in this paper are proof that having optimization sensors that provide information like bending moments, DWOB, etc., are essential to answer tough questions and are key tools in the benchmarking process. Armed with these tools, even the most difficult of wells will have an engineered solution.

More over the authors emphasized on new methods to evaluate reamer dysfunction using the surface and the downhole parameters.

Acknowledgments

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Nomenclature

BHA = Bottom Hole Assembly
BM= Bending Moments
GOM= Gulf of Mexico
DLS = Dogleg Severity
KOP = Kick-off Point
MD = Measured depth
MWD = Measurement while drilling
RSS = Rotary-Steerable System
TD = Total Depth
WOB= Weight on Bit
TOB = Torque on Bit
SS= Stick/Slip
NPT= Non-Productive time
ILT= Invisible lost time
MSE = Mechanical Specific Energy
DH = Downhole
S= Surface

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