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Proven Mud Motor Technology Upgraded for the Digital Age – A Mud Motor with Embedded Sensors Provides Cost-Effective Drilling Dynamics Measurements at Bit Box and Stator Top Sub

Steve Jones and Junichi Sugiura, Scout Downhole / Sanvean Technologies

Abstract
Mud motors are the workhorse of our industry and are utilized on almost every well drilled globally. This makes the mud motor the perfect platform for drilling dynamics measurements at the bit and bottom-hole assembly (BHA).

Proven mud motor technology has been upgraded with miniature cost-effective embedded sensors to measure drilling dynamics at the bit box and stator top sub. The sensors are sized to mount into existing mud motor components without adding length or compromising the mechanical integrity of the components.

The embedded sensors record shock, vibration, rotary speed, toolface and temperature, which are the key dynamic elements to understand downhole dysfunction and energy loss. Mounting the sensors at either end of the mud motor provides two unique data sets of dynamic measurements.

The embedded sensor mud motor enables downhole dynamics mapping on every well drilled on a pad and across the field. Mapping of drilling dynamics on every well provides an understanding of problematic formations and parameters. Systematic changes to bit, BHA and parameters over time provides a clear picture of the right course of action to advance performance toward the technical limit with the ultimate goal of lowering drilling costs.

This paper will explain the mud motor embedded sensors and measurements in detail. Examples of drilling dysfunction recognized and mitigated from evaluation of the downhole embedded measurements will be discussed. The overall performance gains will be evaluated to demonstrate the value of dynamic measurements onboard the mud motor.

Introduction
Steerable drilling motors come in a number of different varieties of lower end (bearing type and transmission) and bent housings (fixed or adjustable and bit-to-bend length) [1]. Power sections continue to evolve, with preference towards slow to medium speed and high torque output [2]. Drilling dynamics measurements were typically not commonplace embedded into mechanical drilling tools until now.

The ability to record key drilling dynamics measurements at the bit box and top sub of the motor (without increasing original motor length, specifically the bit-to-bend length) enables visibility of downhole motor performance. This advantage gives the service company and operator a clear understanding of drilling dynamics at the bit and BHA. Frequently the drilling dynamics experienced at the bit is of higher magnitude than what is recorded in the BHA (either via drilling dynamics carrier subs or measurement-while-drilling [MWD] tools) [3].

With electronics and sensors becoming miniaturized, rugged and cost-effective, this opens up a new generation of drilling dynamics recorder packages that can be embedded into steerable motors and drilling tools.

The sensors are designed to begin recording when the tool is picked up to the rig floor, or sense rotation speed downhole to enable data recording. This makes the embedded sensors practically invisible to normal rig and drilling operations, eliminating the need for specialist personnel on location and no-added time to pick up the BHA [4].

Mud Motor with Embedded Sensors
The latest generation of mud motor has been developed with drilling dynamics sensors embedded into the bit box and top sub as shown in **Figure 1**.

The sensors are installed into existing mud motors without adding additional length, additional connections or compromising the mechanical integrity of the motor. Historically, measurements below the motor required an additional sub between the lower motor connection and the bit [5]. This increases the bit-to-bend length that changes the characteristics of the motor (reduced build rates and different rotary directional response), not to mention the increased side loading applied to the radial bearings of the motor.

The alternative option is to use a bit with built-in sensors, but these are limited to select bit manufacturers that have this capability [4,6-9].

Embedded Sensors

The embedded sensors are designed to be compact enough to fit into existing motor mandrel bit box and rotor catch top sub without having to build new assets. The design allows for modification of existing assets to accept the sensors.

Figure 2 shows the sensor installed in a 4 ¾" motor bit box (although the package is designed to fit into 9 5/8" to 4 ¾" motor sizes). **Figure 3** shows the "puck" shaped sensor package that is screwed into the motor bit box. **Figure 4** shows the sensor package installed into the rotor catch top sub and retained with a hatch cover. **Figure 5** shows the sensor pressure barrel.

Both sensor designs contain the same electronics, solid-state sensors and batteries. The shape of the package is the only difference between the two sensors.

The sensor packages include onboard 3-axis inclinometers (±16G), 3-axis shock sensors (±200G), 3-axis gyros and two temperature sensors. The sensor records burst data to memory every 5, 10, 20, 30, or 60 seconds. The sampling frequency (and anti-aliasing filters) is programmable between 25Hz and 100Hz.

The downhole sensor package has a communication port for set-up and memory dump at the motor service facility. Once the sensors are set-up (e.g. at the repair and maintenance facility), they autonomously start recording while tripping in and while drilling. No interaction with the sensors is necessary at a well-site, minimizing the cost of sensor deployment and making them transparent to rig crews and on-site engineers.

Big Data Versus Small Data and Real-Time Versus Recorded Data

Today big data analytics are widely experimented and practiced in the oil and gas industry [10,11]. On the other hand, "small data" is an amount of data small enough to make it informative and easily accessible and manageable [12]. There is always controversy in the drilling community regarding the best type of data to be gathered downhole and whether this data should be real-time or recorded.

Figure 6 shows the options available for drilling dynamics and mechanics measurements. These can be tiered according to level of service and price.

Doing nothing with downhole drilling measurements leads to anecdotal and opinionated decisions. This is not the most technical and efficient approach and can lead to a long learning curve of trial, error and misinterpretation.

The other options range from basic drilling dynamic recorded measurements (lowest cost) to drilling dynamics/mechanics measurements real-time (highest cost). All these options will cost more than simply doing nothing, so there has to be a balance of expected results and performance gains from each service.

The downhole datasets gathered with compact dynamics recorders are "small data" which are well-structured and go through well-established physics-based equations to be converted to informative processed data, along with surface data or electronic-drilling-recorder (EDR) data.

Proprietary software is used to merge downhole and surface data and provides special visualization tools for data analysis. The software also applies data analytics algorithms to convert "small data" to actionable information as soon as surface and downhole data are loaded into the software. This software and workflow shorten the standard delivery time (several weeks) of processed and actionable information within hours of tools being returned to service base. **Figure 7** shows the basic drilling dynamics measurements recorded at the drilling motor.

Streaming real-time drilling dynamics data at high-speed data rates requires supervision and interpretation by experienced personnel while the well is being drilled. This real-time monitoring and supervision processes can add significant cost to a drilling project, not to mention the reliability of the real-time system. The data is also analyzed post-run to provide recommendations for the next well, adding post-run interpretation and analysis costs as well.

Bear in mind that the complexity and cost of obtaining real-time measurements close to the bit escalates the price significantly. Real-time measurements close to the bit or in the BHA requires wiring of components (or short-hop) [5,13]. Wiring through a drilling motor and BHA adds complexity, reduces reliability and increases overall cost. It may not be viable to run sophisticated real-time measurements in the low-cost land market environment.

To maintain operating costs as low as possible while having the ability to run sensors in multiple locations on every well, the only cost-viable solution is to run basic drilling dynamics recorded measurements.

Time is Money – Fast Processing, Data Viewing and Mapping

Recording the valuable drilling dynamics information (small data) that is easily merged with EDR (Electronic Drilling Recorder) provides cost-effective information that can lead to significant improvements in drilling practices and overall time to drill the well.

Data is delivered to the operator as a data file-set that contains downhole data merged with surface EDR. Proprietary software is used to merge and display the data in easily read tracks and traces.

Historically drilling dynamics logs are viewed in track and trace format using PDF (Portable Document Format). This can make it difficult to analyze the data as there is no freedom to zoom in on areas of interest and change the track scales. The software also allows the user to “read” the value of the curve when the cursor is pointed. The proprietary software is available as a “viewer” that enables the operator to change scales and zoom-in on regions of interest. Data from other third-party devices used in the BHA can be imported and used for full drilling dynamics analysis.

One of the biggest complaints with handling drilling data sets is the time and effort required to get the data into a usable format for analysis. The proprietary “viewer” eliminates the time spent configuring and merging data, thus reducing the time required by the Drilling Engineer or Optimization Engineer. The tailored viewing package makes data analysis much more efficient.

Mapping the drilling dynamics data recorded from each well drilled on a pad provides a roadmap of the best drilling practices and downhole products utilized. This technique is cost-effective and suitable for high-volume shale drilling development.

Software Viewer – Log Plot

Figure 8 shows the software viewer display explaining the main parameters that are displayed from a mud motor with embedded sensors. **Table 1** explains the mnemonics used on the viewer.

This example data set is from a clean 8 ½” lateral run with no drilling dysfunction.

Example #1

A 6 ¾” instrumented motor was used to drill an 8 ½” hole at low angle. **Figure 9** shows a snapshot of data and the associated regions of interest, and causes are listed in **Table 2**.

From this example, there is a strong-intensity lateral frequency signal of 8Hz at the motor top sub. This also aligns with an increase in calculated revolutions per minute (RPM) at the motor sub top indicating that whirl is likely present in the motor/BHA. The lateral shocks at the motor bit box also increase to high sustained values when this condition is present.

A closer look at the surface parameters indicates that the weight on bit (WOB) was increased from 35Klbs to 40-45Klbs when this downhole dysfunction was present. The onset of whirl in the BHA resulted in lower rate of penetration (ROP) in this particular case.

Sustained whirl for a long period of time increases the risk of BHA failure and bit damage. Changes to WOB, surface RPM settings and stabilization for subsequent runs/wells would allow the data to be analyzed again to determine if the changes have reduced the dysfunction and improved overall drilling performance.

As can be seen from this example, small changes in surface parameters can have a detrimental impact on downhole BHA stability. These dysfunctions cannot be identified at surface. However, the use of embedded sensors provides a clear picture of the actual dysfunctional condition downhole. Small systematic changes to parameters, BHA and bit can lead to a more efficient drilling system and reduce overall drilling costs.

Example #2

Example #2 is from a 6 ¾” motor drilling an 8 ½” lateral section. The case presented in **Figure 10** is a snapshot of data associated with regions of interest, and causes are listed in **Table 3**.

This example sustains moderate levels of stick-slip (60%) throughout the run. The stick-slip percentage is computed based on the equation provided by Macpherson et al [14]. High levels of lateral and axial shocks are observed at the bit box at the start of the interval. These high levels of shock correlate with a temperature rise at the bit box. A temperature rise of up to 36°C (96.8°F) is noted between the bit box and top sub. The increase in temperature at the bit box is sustained for the duration of the high shocks.

Part way through the interval the WOB and flowrate are increased. The high lateral and axial shocks at the bit remain until the BHA is buried into new hole with the new parameters, then the lateral and axial shocks at the bit return to low levels. The reduction in shock at the bit box correlated with a reduction in temperature at the bit box. Both temperature at the top sub and bit box became the same.

The temperature rise at the bit was significant and sustained for a long enough period of time that damage to the lower end of the motor or lower end of the stator elastomer could have resulted.

Changing WOB and flowrate had a positive effect in reducing the shock experienced at the bit. ROP did not increase significantly when the shock levels reduced, however the reduced shock and elimination of temperature rise ultimately helped preserve the bit and motor enabling a longer run.

This example clearly shows that parameter changes can have a significant effect on the dynamics present at the bit. The high shocks and temperature rise could not have been measured by a sensor above the motor (i.e. MWD) and would have gone un-noticed for the entire run.

Example #3

This case is taken from a 6 ¾” instrumented motor drilling an 8 ½” lateral section. **Figure 11** shows an example of data associated with regions of interest, and causes are listed in

Table 4

This data set is focused on a slide interval. The bit-box RPM (from a gyro) is displayed as maximum and minimum values from the burst data to closely evaluate RPM response.

It can be seen from the data that there are several hard motor stalls indicated by a sudden increase in differential pressure. At the same time the bit RPM reduced to zero and there was an increase in lateral shock at the bit.

There are also multiple events where the RPM at bit reduced to zero but there was no increase in differential pressure at surface that would have indicated a motor stall downhole. Following the stall the bit released and bit rotation speed increased up to 240 RPM. High sustained lateral shocks were present at the bit during this interval.

No negative-RPM (reverse-rotation) events were noted throughout the dysfunctional sections while slide drilling. Note that negative-RPM events are common during a motor and/or string stalls while rotary drilling [4].

This data set clearly shows a sequence of dysfunctional events that would not be seen from sensors placed above the motor. It is evident that weight transfer from surface to bit is inconsistent due to the drag being experienced along the lateral. The use of a friction-reduction tool (e.g. SPE-178792) placed in the correct location would likely improve weight transfer and reduce bit stalling and dysfunction at the bit [3].

Conclusions

The application of embedded drilling dynamics sensors in a mud motor bit box and top sub delivers a unique data set that can identify dysfunction below and above the motor. The dysfunction at the bit is not seen from sensors above the motor, for example, from MWD.

The embedded drilling dynamics sensors have been designed to be cost-effective (compared to drilling mechanic measurements and real-time systems). This enables the sensors to be run on every well to enhance the learning curve, rather than just occasional wells where higher cost systems are typically used.

Running sensors embedded into the motor on every well delivers a portfolio of data for comparison and optimization purposes. Mapping of this data leads to a "smart landscape" of drilling dynamics response to aid decision making and ultimately reach the technical limit faster. Continuous improvements can be executed well by well.

Delivery of downhole data merged with EDR utilizing a proprietary viewer provides the Drilling Engineer and/or Optimization Engineer with a data set that is immediately usable. The ability to zoom-in on sections of data and change track/trace scales enhances the data analysis experience and time/effort required.

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Nomenclature

BHA = *Bottom-Hole Assembly*
DLS = *Dogleg Severity (degrees per 100 feet)*
DOC = *Depth Of Cut*
EDR = *Electronic Drilling Recorder*
GPM = *Gallons Per Minute*
MD = *Measured Depth*
MSE = *Mechanical Specific Energy*
MWD = *Measurement While Drilling*
PDC = *Polycrystalline Diamond Compact*
PDF = *Portable Document Format*
ROP = *Drilling Rate Of Penetration*
RPM = *Revolutions Per Minute*
TD = *Target Depth*
WOB = *Weight On Bit*

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Figure 1: Mud Motor with Embedded Sensors in Bit Box and Top Sub

Figure 2: Sensor Installed in Motor Bit Box

Figure 3: At-Bit Sensor Installed in a “Puck” Shaped Package

Figure 4: Top Sub Sensor Installed under Hatch Cover (Hatch Cover is Transparent to View Sensor)

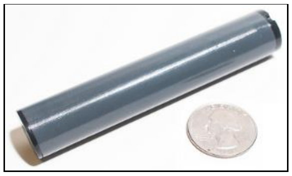

Figure 5: Top Sub Sensor in Pressure Housing

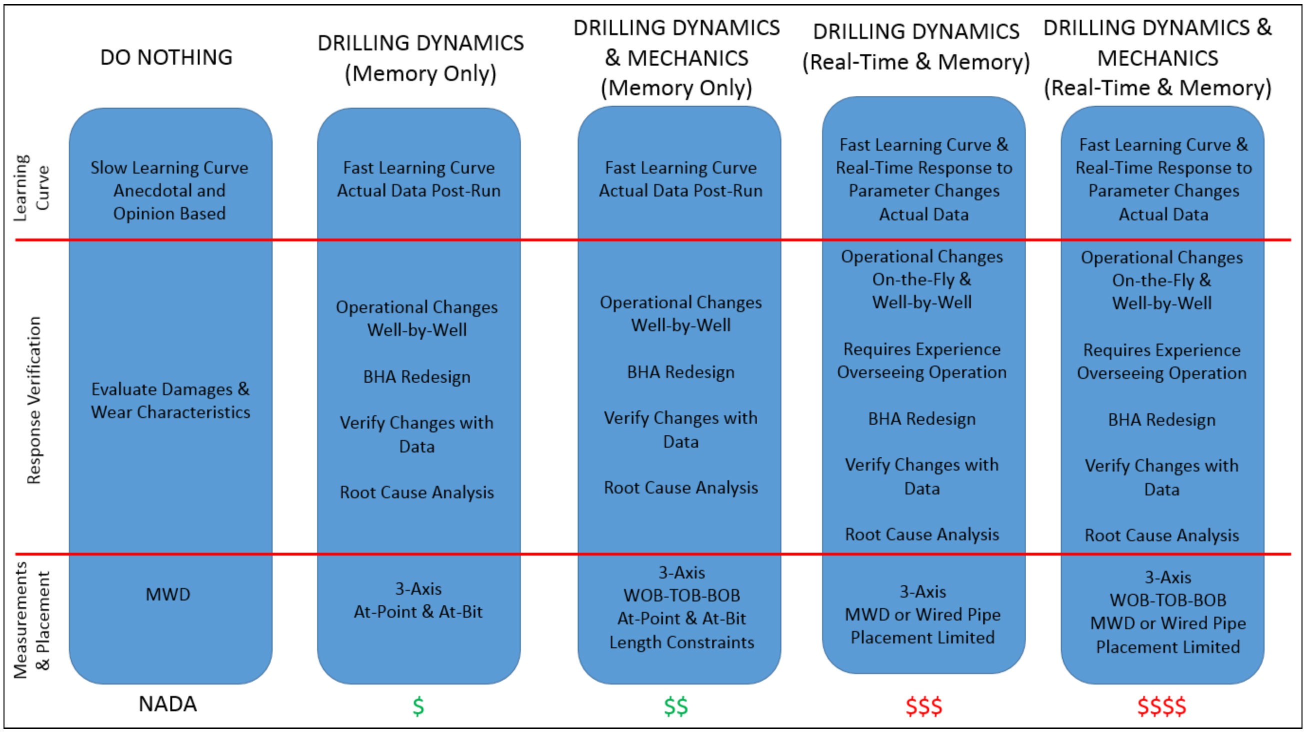

Figure 6: Drilling Dynamics and Mechanics Landscape

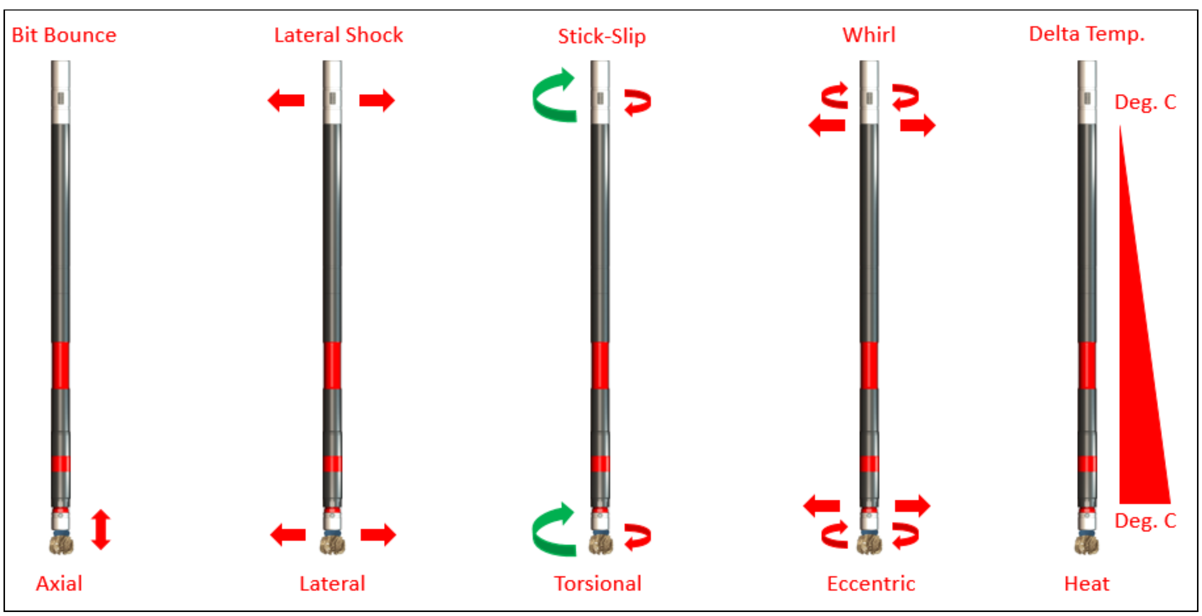

Figure 7: Basic Drilling Dynamic Dysfunctions Measured at Embedded Sensors

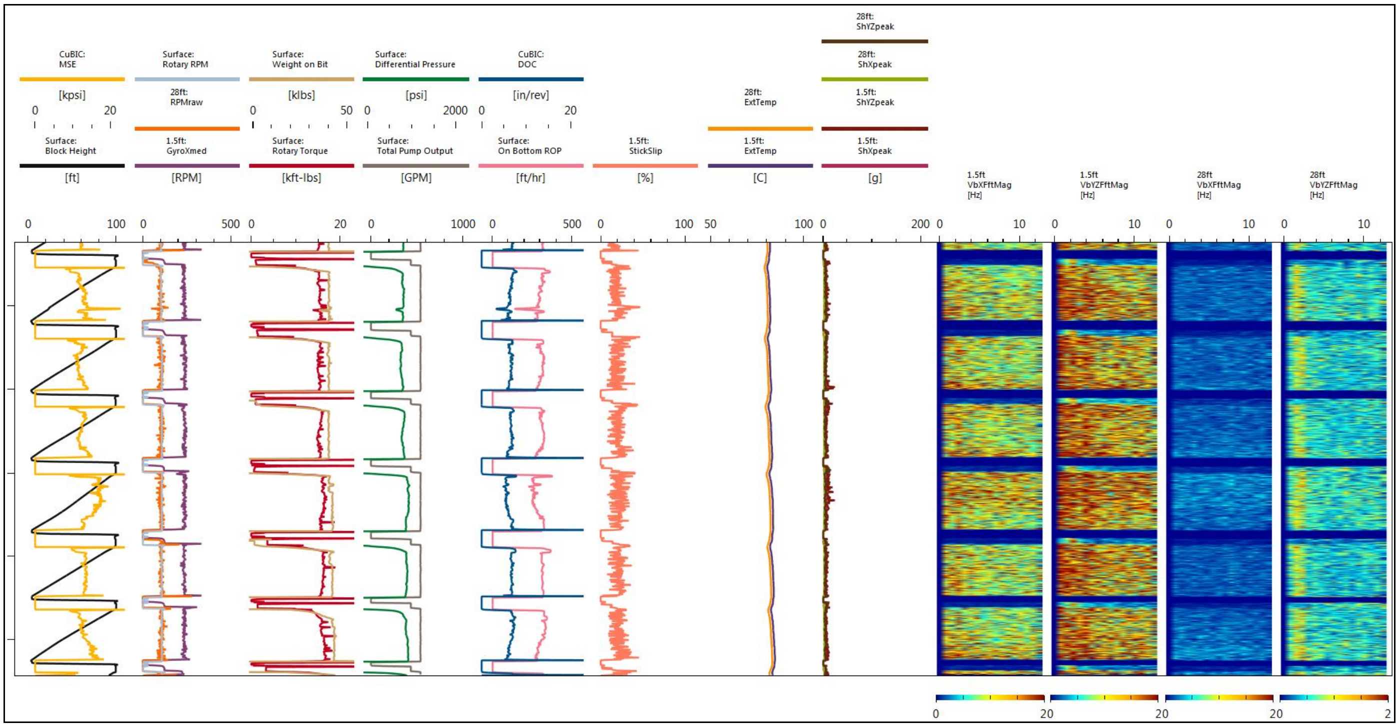

Figure 8: Software Viewer – Sample Data Set

Table 1: Software Viewer - Mnemonics Description

Track	Trace	Description
1	MSE	Mechanical Specific Energy calculated using RPM measured at bit (kpsi)
1	Surface Block Height	Surface block height from EDR (ft)
2	Surface Rotary RPM	Surface rotary RPM from EDR (rpm)
2	28ft RPMraw	Calculated RPM from sensor in motor top sub (rpm)
2	1.5ft GyroXmed	Measured RPM at motor bit box (rpm)
3	Surface Weight on Bit	Surface weight on bit from EDR (klbs)
3	Surface Rotary Torque	Surface rotary torque from EDR (kft-lbs)
4	Surface Differential Pressure	Surface differential pressure from EDR (psi)
4	Surface Total Pump Output	Surface total pump output from EDR (gpm)
5	DOC (depth of cut)	Calculated depth of cut (in/rev)
5	On Bottom ROP	On bottom rate of penetration from EDR (ft/hr)
6	1.5ft StickSlip	Stick-slip calculated at bit (%)
7	28ft ExtTemp	Measured temperature at motor top sub (°C)
7	1.5ft ExtTemp	Measured temperature at motor bit box (°C)
8	28ft ShYZpeak	Peak lateral shock at motor top sub (g)
8	28ft ShXpeak	Peak axial shock at motor top sub (g)
8	1.5ft ShYZpeak	Peak lateral shock at motor bit box (g)
8	1.5ft ShXpeak	Peak axial shock at motor bit box (g)
9	1.5ft VbXFftMag	Axial frequency spectrum at motor bit box (Hz and Intensity)
10	1.5ft VbYZMag	Lateral frequency spectrum at motor bit box (Hz and Intensity)
11	28ft VbXFftMag	Axial frequency spectrum at motor top sub (Hz and Intensity)
12	28ft VbYZMag	Lateral frequency spectrum at motor top sub (Hz and Intensity)

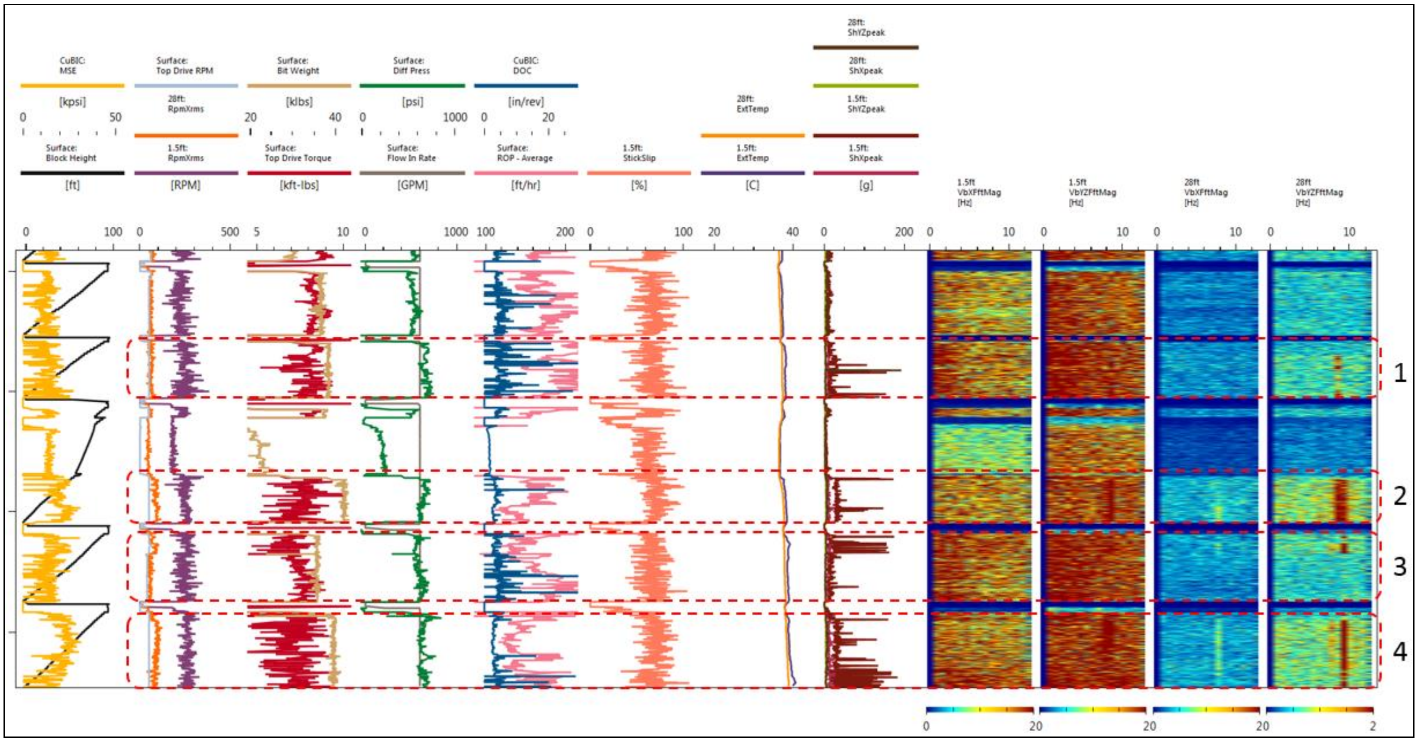

Figure 9: Example #1 – Whirl at Motor Top Sub, High Lateral Shock at Motor Bit Box

Table 2: Example #1 – Regions Identified and Cause

Region	Identified	Cause
1	Whirl at top sub seen on lateral frequency spectrum Intermittent spikes in lateral shock at bit up to 140g	Increased WOB from 35Klbs to 40Klbs
2	Wider band whirl at top sub seen on lateral frequency spectrum Whirl also seen at bit on lateral frequency spectrum Sustaining 40g lateral shock at bit with spikes up to 170g Downhole RPM registering 30RPM above surface RPM ROP slower than previously	Increased WOB to 42Klbs
3	Whirl indication at top sub disappears Lateral shocks at bit reduce to less than 20g	Reduced WOB to 35Klbs Surface RPM increased briefly to 60 RPM
4	Whirl at top sub seen on lateral frequency spectrum Sustaining 40g lateral shocks at bit then sustaining 140g Downhole RPM registering 50RPM above surface RPM ROP slower than previous parameters	Increased WOB to 40Klbs

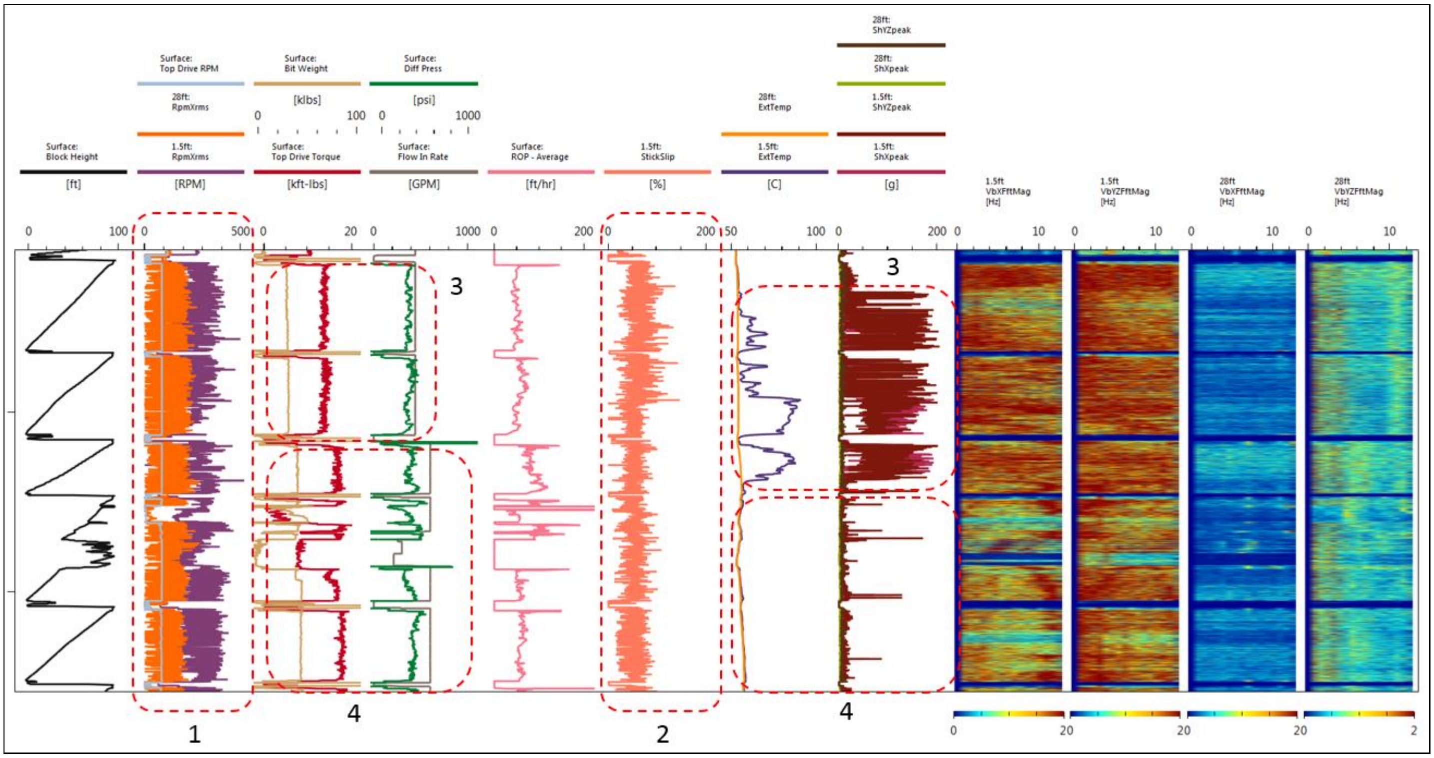

Figure 10: Example #2 – High Lateral/Axial Shocks at Bit Box and Associated Temperature Rise

Table 3: Example #2 – Regions Identified and Cause

Region	Identified	Cause
1	Wide band of RPM at bit box and top sub	Unknown, sustained for majority of run
2	Averaging 60% stick-slip throughout run	Unknown, sustained for majority of run
3	High sustained lateral and axial shocks at bit box, up to 200g Corresponding temperature rise at bit box. Up to 36°C (96.8°F) difference in temperature between bit box and top sub.	WOB 14Klbs, Flowrate 440GPM
4	Lateral and axial shock at bit box returns to low levels. Temperature at bit box and top sub return to the same values.	Increased WOB to 18Klbs and increased flowrate to 600GPM

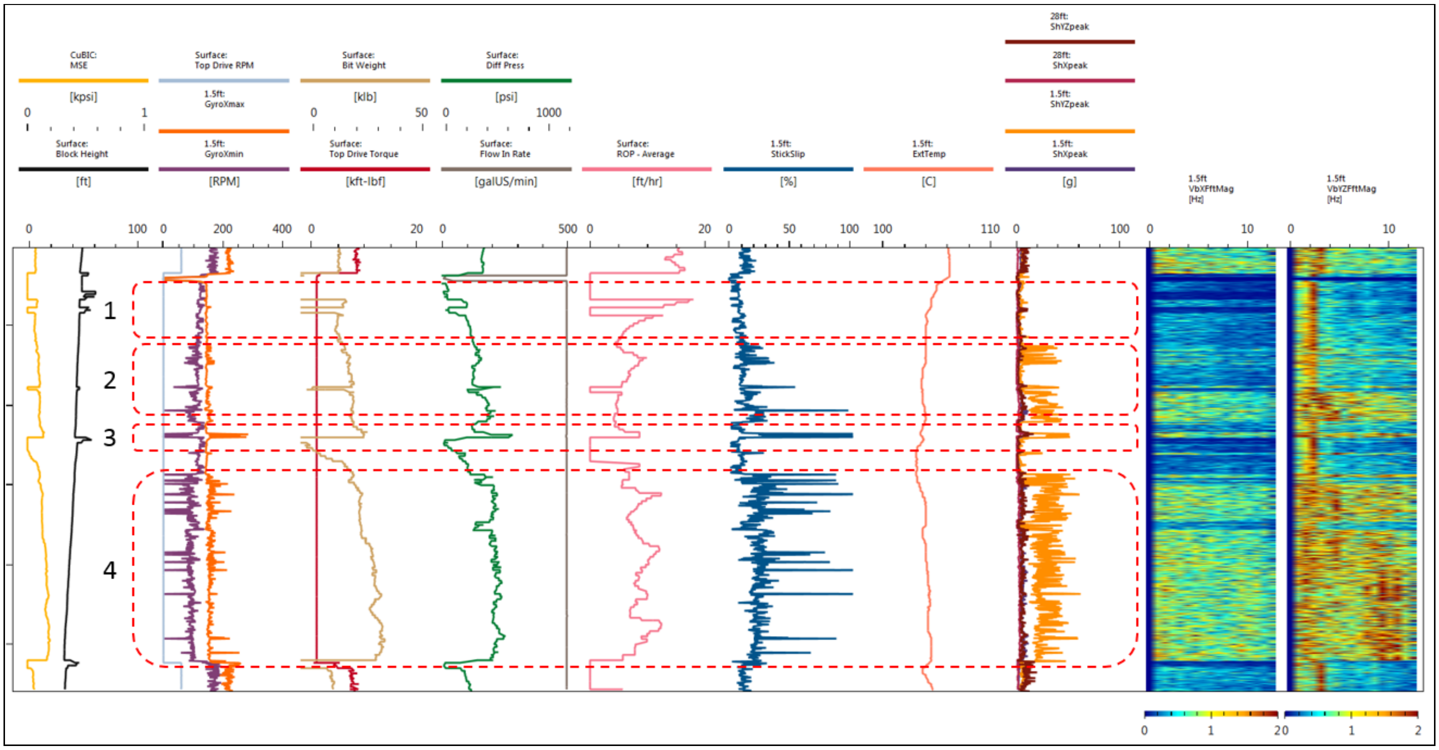

Figure 11: Example #3 – Bit Stalling While Sliding

Table 4: Example #3 – Regions Identified and Cause

Region	Identified	Cause
1	Smooth sliding with no stick-slip or shock	N/A
2	Onset of wider RPM spread (70-170 RPM). Wider RPM spread correlates with higher lateral shock at bit box (40g). Picked-up once due to differential pressure increase (530 PSI), bit speed slowed to 30 RPM.	Surface WOB increased from 14Klbs to 19Klbs.
3	Hard motor stall. Differential pressure increased to 650 PSI. Bit RPM goes to zero. Bit releases to 285 RPM. Lateral shock 52g.	Surface WOB increased from 18Klbs to 25Klbs.
4	Multiple events of bit stalling to zero RPM. Sustained lateral shocks up to 50g. No increase in differential pressure seen at surface. Erratic ROP during intervals when bit rotation zero. High stick-slip at bit.	Suspect inconsistent weight transfer to bit.