

Real-Time Stick-Slip and Vibration Detection for 8 ½"-Hole-Size Rotary Steerable Tools in Deeper Wells and More Aggressive Drilling

Junichi Sugiura, Steve Jones — PathFinder Energy Services

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Abstract

In an extended-reach and horizontal well drilling environment, stick-slip becomes increasingly problematic with smaller-diameter and longer drillstrings. Surface detection of the bottom-hole assembly stick-slip and vibration becomes ever more difficult. A Real-time Stick-slip and Vibration Detection (RSVD) system was incorporated into a new 8 ½-inch-hole-size Rotary Steerable System (RSS), to increase drilling efficiency in deep wells and to protect the RSS and the MWD/LWD tools from harmful vibrations.

This RSVD system is an innovative near-bit vibration sensor integrated into the RSS, featuring detection of the three principal modes of drillstring vibration — torsional, lateral and axial. The sensor is located 8.2 feet above the bit in the push-the-bit configuration and 11.1 feet above the bit in the point-the-bit configuration. The system sends the detected stick-slip severity to the surface in real time so that operators can change drilling parameters if harmful downhole conditions are detected.

In 2006, the new sensor system was extensively tested and proved to be effective with the new 8 ½"-hole-size RSS in various wells, including vertical and horizontal, both onshore and offshore. This paper will discuss the harmful stick-slip and vibration conditions in smaller-hole-size wells and how the RSVD system improved penetration rate and prolonged the optimum performance of the drill bit, BHA, MWD/LWD, and rotary steerable tool in various situations.

Introduction

Research on drillstring dynamics has been extensively conducted in the past [1-4]. In the 1980's and 1990's, drillstring dynamics MWD sensors were developed to detect and record harmful downhole vibrations [5-16]. Today, it is well known that severe downhole vibrations can damage drilling equipment including the drill bit, drill collars, stabilizers, MWD/LWD, and Rotary Steerable System (RSS).

In 1997, the first introduction of the commercial RSS revolutionized directional drilling [17]. Since then, RSS technology has made remarkable improvements in reliability and has become a mature, standard application. Nevertheless, due to its inherent complexity, the reliability of the RSS is still lower than that of MWD and LWD tools [18].

In 2005, PathFinder developed a new RSS for 8 ½" hole size, based on proven 12 ¼"-hole-size RSS technology, for

drilling more challenging extended-reach and horizontal wells. The new RSS consists of a non-rotating housing with three active and independent blades that maintain constant contact with the wellbore. Directional steering is achieved by positioning the blades to offset the tool center from the centerline of the hole. Therefore, the system drills a continuous curve and does not rely upon on/off biasing. The constant contact of the blades with the borehole provides near-bit caliper measurements and, moreover, extra stability to the lower part of the bottom-hole assembly (BHA) hence reducing undesirable drill bit vibrations and instability [19].

Despite the extra stability gained at the RSS, it is inevitable that the tool is exposed to high vibrations due to, for example, torsional vibration (stick-slip) induced from the bit-formation interaction [2,11,13], lateral vibrations caused by the mass imbalance of drill collars and other BHA components [12,20], and axial vibrations resulting from the high-low pattern of a rock bit in hard formation [1,14]. Moreover, some of these vibrations do not travel to the surface.

Thus, Real-time Stick-slip and Vibration Detection has been incorporated into the newly developed 8 ½"-hole-size RSS. The new sensor system is designed to detect near-bit vibration at the RSS. Timely remedies to harmful vibrations can protect MWD/LWD and the RSS from such vibrations and increase drilling efficiency [16,20-24]. With the RSVD system, the operator can be aware of harmful downhole conditions and can adjust surface parameters, such as RPM, WOB and flow rate, to optimize the drilling performance. This system is a unique near-bit vibration sensor integrated into the RSS, featuring the detection of three principal modes of the drillstring vibration, namely torsional, lateral and axial.

Design Concept

The Real-time Stick-slip and Vibration Detection system has been integrated into the new 8 ½-inch-hole-size RSS tool to detect harmful downhole vibrations. The new sensor system utilizes the existing hardware (rotation and vibration sensors) of the RSS to quantify the severity of downhole torsional (stick-slip), lateral and axial vibrations.

Figure 1 shows the 8 ½"-hole-size point-the-bit RSS with the RSVD system. All three principal modes of the drillstring vibration are detected at the RSS and classified into 4 categories of severity for the band-limited mud pulse telemetry. Also, this classification produces effective data

compression. The new sensor system is designed to be used for all the RSS runs. Therefore, it is crucial that uplink communication bandwidth of the vibration information be minimum.

The Stick-slip Severity (SS%) is computed from the drill bit rotation sensor and expressed as:

$$SS \% = \frac{|\Delta RPM|}{MeanRPM} \times 100 \% \quad \dots \text{Equation 1}$$

The drill bit rotation variation (ΔRPM) is normalized with an average rotation rate (MeanRPM) of the drill bit. Dufeyte et al. first used a similar equation for the surface detection of the stick-slip phenomenon [8]. The SS% is further classified into 4 different severity levels.

Table 1 below shows the stick-slip level, classification, and percentage severity. Stick-slip levels between 0 and 3 are sent to the surface via mud pulse telemetry.

Table 1. Stick-Slip level, classification and percentage severity

Stick-Slip Level	Stick-Slip Classification	SS %
0	Very Low	0 ~ 50%
1	Low	50% ~ 100 %
2	Medium	100 % ~ 150 %
3	High	150 % or more

The Lateral Vibration Severity ($Vib_{xy}\%$) is computed from the x- and y-axis acceleration sensors and expressed as:

$$Vib_{xy} \% = |\Delta Vib_{xy}| \times Scale \times 100 \% \quad \dots \text{Equation 2}$$

The lateral vibration fluctuation (ΔVib_{xy}) is scaled and converted into percentage severity ($Vib_{xy}\%$). The scale factor in **Equation 2** was fine-tuned through extensive field tests where the correlation between vibration levels and the RSS dysfunctions was identified.

Similarly, the Axial Vibration Severity ($Vib_z\%$) is computed from the z-axis acceleration sensor and expressed as:

$$Vib_z \% = |\Delta Vib_z| \times Scale \times 100 \% \quad \dots \text{Equation 3}$$

These lateral and axial vibration severities, in percentage, are classified into 4 categories as in the stick-slip level.

Table 2 below shows the vibration level and classification. Vibration levels between 0 and 3 are sent to the surface via mud pulse telemetry.

Table 2. Vibration level, classification and percentage severity

Vibration Level	Vibration Classification	Vib %
0	Very Low	0 ~ 25%
1	Low	25% ~ 50 %
2	Medium	50 % ~ 75 %
3	High	75 % or more

Since the RSVD system utilizes the existing hardware of the RSS, the new sensor has added no extra complexity into

the RSS. Moreover, this design approach enables a cost-effective near-bit dynamics sensor, which is presently a standard component of all PathFinder's rotary steerable tools.

The system also transmits the detected severity to the surface with real-time mud pulse telemetry so that operators can change drilling parameters if harmful downhole vibrations are detected. This feature, along with the near-bit caliper measurement, resulted in increased overall reliability and performance of the RSS and other drilling equipment.

Detected Downhole Vibration Problems

PathFinder has conducted a series of extensive field tests with the 8 1/2"-hole-size rotary steerable systems (RSS) in 2005 and 2006. The new RSS, along with the RSVD feature, detected various downhole vibration conditions. This section shows some of the most commonly observed harmful vibration cases. When a downhole failure occurred, vibration information stored in memory was used for more detailed post-run analysis, the root cause of the failure was investigated, and the failed component was redesigned for more durability.

Full-Stall Stick-Slip

Figures 2 and 3 illustrate the full-stall stick-slip observed on a rig in the Gulf of Mexico while drilling in a "ratty" abrasive sandstone section with the 8 1/2"-hole-size RSS. Post-drilling LWD data analysis showed that this section was composed of high salinity siltstone, shale, and sand. Very slow drilling (low ROP) and high/erratic string torque between 10 to 25K ft-lb were encountered.

Figure 2 shows surface parameters/data during downhole full-blown stick-slip. **Figure 3** shows downhole-computed mean and raw RPM vs. blade housing toolface angle. It is noticed that rotary torque correlated highly with the downhole stick-slip data while the WOB was kept nearly constant. The Set_RPM is the programmed surface RPM that is different from the actual surface RPM (not shown).

In **Figure 3**, the slowly changing BL1_TF (blade housing toolface angle between 140 and 170 degrees) indicates that the non-rotating blade housing was substantially stationary as compared with the drillstring rotation (about 120 RPM). During the stick-slip period, the maximum raw RPM (240 ~ 360 RPM) was 2 or 3 times higher than the surface RPM (\approx 120 RPM). The corresponding Stick-slip Severity (SS%) in the period is approximately between 200% and 300%.

Polycrystalline Diamond Compact Bit Comparison

Figures 4 and 6 show the examples of bit-formation induced stick-slip on the 8 1/2"-hole-size RSS observed in Oklahoma. Mean_RPM, Raw_RPM, and BL1_TF represent average near-bit RPM, raw near-bit RPM, and Blade 1 toolface, respectively. The slowly changing BL1_TF indicates that non-rotating blade housing is substantially stationary.

A 7-bladed bit with 13mm (1/2-in) PDC cutters shown in **Figure 5** was used in the run (Run # 16). This PDC bit (with 1.5" active gauge) produced ROP less than 9 feet/hour and the decision was made to change for a more aggressive drill bit to

increase ROP.

A 6-bladed bit with 16mm (5/8-in) PDC cutters shown in **Figure 7** was used in this run (Run # 17). This bit (with 3" passive gauge) produced an average ROP of 15 feet/hour. The ROP was almost doubled while the formation and the surface parameters were practically identical. However, with a more aggressive bit, near-bit RPM varied roughly by ± 40 RPM (Stick-Slip Severity was about 72%). This stick-slip problem became worse while drilling through different formations and eventually resulted in premature failure of the RSS.

This is a classical case in which the optimization for maximum penetration rate resulted in damage to the drilling equipment, thus a costly trip (round trip) and non-productive time (down time) due to vibration-related premature failure.

PDC and Rock Bit Comparison

The GTI Test Facility in Catoosa, Oklahoma was used to evaluate the prototype 8 1/2"-hole-size RSS for performance, ruggedness and reliability. **Figure 8** shows real-time MWD and RSS vibration data collected at the GTI facility, including the surface parameters. The MWD vibration data was measured approximately 45 feet above the bit, providing the number of vibration counts above 20 G per second.

Vibration profiles between a PDC and a rock bit (a roller cone bit) are compared using the RSVD system. The PDC bit induced more lateral vibrations, whereas the rock bit produced more axial vibrations. The real-time vibration data (Lateral Vibration = Low and Axial Vibration = Low) obtained with the RSVD system at the RSS correlated highly with the vibration counts (≈ 100 counts/second ... considered as a low vibration count) detected at the conventional MWD tool. While drilling through a hard dolomite section, called the Arbuckle group (not shown), this BHA suffered from high vibration counts (≈ 450 counts/second) and high near-bit lateral vibration at the RSS. This vibration problem eventually resulted in RSS failure.

Lateral Vibration due to Mass Imbalance

At the GTI Catoosa facility, medium-to-high vibration severity was detected with both MWD and the RSVD system while the 8 1/2"-hole-size RSS was drilling in a dolomite section. The Run #1 BHA was initially configured for drilling a high-inclination well (i.e. a horizontal well). 20 joints of 5" heavy-weight drill pipe (HWDP) were used below 10 joints of 6 1/4" drill collars. **Figure 9** shows high lateral and axial vibrations at the RSS in Run #1. The near-bit caliper measurement indicated that hole was in gauge, between 8.54" and 8.56". The near-bit RPM measurement was steady at approximately 100 RPM. There was no sign of stick-slip phenomenon (SS3D = 0). The slowly changing BL1_TF indicated that the non-rotating blade housing was substantially stationary, providing additional stability to the BHA. At this point, the exact cause of the vibration problem was unknown.

Long and repetitive exposure to excessive shock and vibration is harmful to the RSS and, in the worst case, catastrophic. Thus, different surface parameters were varied to reduce vibrations using the RSVD information, but all

attempts ended unsuccessfully. The decision was made to pull out the tool to change the position of drill collars and heavy-weight drill pipe (HWDP). The BHA order was inverted, for example, 10 joints of 6 1/4" drill collars were run below 20 joints of 5" HWDP. At the same time, the onset of drilling equipment damage was discovered and repaired at the rig site.

While repairing, a back-up tool with a rock bit was used in Run #2 (not shown) without BHA modification to see whether the rock bit reduced excessive vibration. This bit change did not reduce vibration.

In Run #3, the repaired tool from Run #1 with the BHA modification was tripped in and commenced drilling. **Figure 10** shows that the RSS vibration in Run #3 was reduced by almost half from Run #1 while the same RPM and WOB were used. In both runs, the borehole inclination was between 19 and 20 degrees. The formation drilled in Run #3 was similar to that of Run #1.

Figure 11 shows the surface parameters and the real-time data measured with the RSVD system. Both lateral and axial vibration severity levels were suppressed to Level 1 (Low Severity). Moreover, the real-time MWD vibration counts were reduced from 300 CPS to 50 CPS. It was concluded that BHA mass imbalance and BHA instability created high lateral vibrations in Run #1.

Customer Well Results

In 2005 and 2006, the RSVD system integrated into the 8 1/2"-hole-size RSS was extensively tested in various customer wells in North America, including vertical and horizontal wells, onshore and offshore. As of December 25, 2006, the newly designed 8 1/2"-hole-size RSS has drilled 42,055 feet, accumulating 1,738 operating hours. Throughout the commercial pilot runs, the real-time drilling screen was available to a multi-disciplinary drilling optimization team consisting of a Directional Drilling Engineer, an RSS Optimization Engineer, a Research Engineer and a Design Engineer. Remote satellite communication and Internet technologies enabled the team to monitor the downhole drilling conditions around the clock. This team provided critical feedback to the on-site Directional Drillers and MWD Engineers for minimizing vibration-related failures and for improving drilling efficiencies.

The following section discusses how the RSVD system improved ROP and prolonged the optimum performance of the drill bit, BHA, MWD/LWD, and rotary steerable tool in three examples of customer wells.

Well A

The vertical section of an S-shape well was drilled with the fully automated 8 1/2"-hole-size RSS in Texas. The borehole inclination was originally 1.06 degrees. The RSS quickly dropped the inclination back to less than 0.1° and maintained the inclination to an average value of 0.05° for approximately 1,000 ft. The average inclination of the near-vertical borehole was based upon the MWD static surveys. No time was wasted downlink programming the RSS in this vertical drilling application as the RSS was set up to

continuously seek low-side. Several rig repairs were carried out during 3 days, adding non-productive time. The overall penetration rate in the vertical section was 14.1 ft/hr.

While drilling, the RSVD revealed that excessive stick-slip hindered ROP on this well. **Figure 12** shows the near-bit inclination, bit RPM and Stick-slip Severity in % computed at the RSS. The downhole computer applies a low-pass filter to raw RPM readings and records a mean RPM in memory. It was noticed that the filtered RPM was still noisy due to stick-slip.

The RSS assembly was pulled for low ROP and a suspected undergauge bit. At surface, bit and near-bit stabilizer were both undergauge. The following run was a conventional steerable motor with a similar PDC bit. This assembly averaged 23 ft/hr indicating that stick-slip was causing the low ROP. In this application, the use of a motor-assisted RSS assembly would have reduced stick-slip at the bit and ultimately led to improved ROP.

Well B

The 8 1/2"-hole-size RSS was used with a small under-powered rig in New Mexico. The RSS drilled 3,260 ft at an ROP of 39.7 ft/hr, accumulating 82.2 drilling hours and 164.2 circulating hours. WOB was maintained at 15,000 to 20,000 lbs. No major vibrations were observed in the first half of the run as shown in **Figure 13**. In the second half, stick-slip became problematic with Stick-slip Severity between 100% and 200%. Very little lateral and axial vibrations were observed in the real-time data. The RSS operators were able to manage the stick-slip problem and completed 1,700 ft of the problematic footage without downhole failure.

These wells are typically drilled at an average ROP of 15 ft/hr with a conventional steerable motor and rock bit (for steerability). The use of RSS and PDC bit provided a 164% increase in ROP.

Well C

The 8 1/2"-hole-size RSS was used on the build section of a Fayette Shale well. The well plan called for 8°/100ft build rates to land in the reservoir at 92 degrees as shown in **Figure 14**. Due to rig rotary speed (RPM) limitations, this well was drilled with the RSS below a slow-speed downhole motor and a PDC bit. The well was kicked off and built angle at 8°/100ft using an 80% offset setting. The RSS offset setting was reduced as the angle increased to maintain the desired 8°/100ft build rates. Both stick-slip and vibration were low throughout the run as a result of using the motor-assisted RSS assembly. The assembly drilled 1,404 ft at an average ROP of 55 ft/hr.

Typically these wells are drilled at an average ROP of 30 ft/hr with a conventional steerable motor and rock bit (for steerability). The use of motor-assisted RSS and PDC bit produced an 83% increase in ROP and a significant reduction in stick-slip and vibration.

Conclusion

- The Real-time Stick-slip and Vibration Detection system, integrated into the newly designed 8 1/2"-hole-size RSS, is a cost-effective near-bit vibration sensor, which is now a standard component of all tools. The sensor system was effective for detecting various downhole dynamic conditions in real time.
- The real-time near-bit stick-slip and vibration data, along with near-bit caliper measurements, is always available to Directional Drillers and MWD Engineers while drilling complex 3D wells using an RSS. The sensor system leads to optimized drilling parameters in most of the RSS runs by avoiding under-utilization of the vibration information.
- The customer well results indicated that the RSVD feature helps minimize the detrimental effect of downhole vibrations and prolong optimum performance of the RSS and other BHA components. The effective use of the sensor system resulted in increased reliability of the RSS.
- The use of aggressive bits and aggressive drilling parameters do not necessarily increase the overall ROP due to increased chance of downhole failures and consequently increased non-productive down time.
- The use of less aggressive but stable bits and optimized drilling parameters with manageable vibration levels helps improve the overall ROP and reduce downhole failures.
- The use of motor-assisted RSS and PDC bit reduces stick-slip and vibration and further improves penetration rate.
- The improved drilling performance and time/cost saving obtained with the RSVD feature are significant.

Acknowledgments

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Nomenclature

<i>BHA</i>	=	<i>Bottom Hole Assembly</i>
<i>CPS</i>	=	<i>Counts Per Second</i>
<i>DLS</i>	=	<i>Dogleg Severity (degrees per 100 feet)</i>
<i>GPM</i>	=	<i>Gallons Per Minute</i>
<i>HWDP</i>	=	<i>Heavy-Weight Drill Pipe</i>
<i>LWD</i>	=	<i>Logging While Drilling</i>
<i>MD</i>	=	<i>Measured Depth</i>
<i>MWD</i>	=	<i>Measurement While Drilling</i>
<i>NB</i>	=	<i>Near Bit</i>
<i>PDC</i>	=	<i>Polycrystalline Diamond Compact</i>
<i>ROP</i>	=	<i>Drilling Rate Of Penetration</i>

<i>RPM</i>	=	<i>Revolutions Per Minute</i>
<i>RSS</i>	=	<i>Rotary Steerable System</i>
<i>SS%</i>	=	<i>Stick-slip Severity in Percentage</i>
<i>TD</i>	=	<i>Target Depth</i>
<i>TORQUE</i>	=	<i>Surface Measured Torque</i>
<i>TVD</i>	=	<i>True Vertical Depth</i>
<i>VS</i>	=	<i>Vertical Section</i>
<i>WOB</i>	=	<i>Weight On Bit</i>

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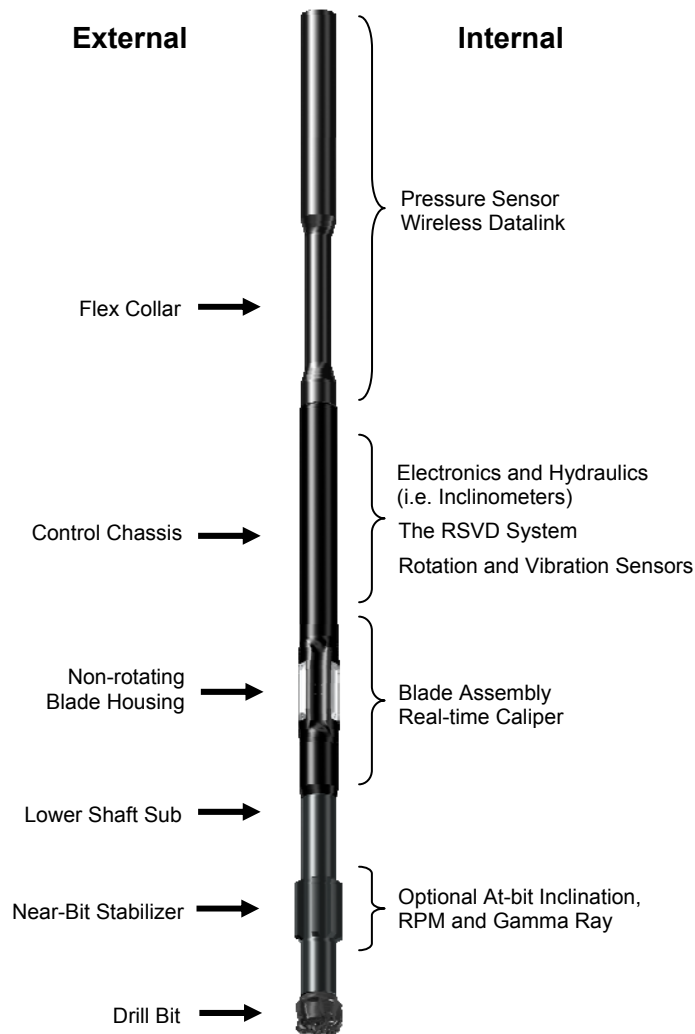


Figure 1. The Real-time Stick-slip and Vibration Detection (RSVD) system integrated into the 8 1/2-inch-hole-size RSS in a point-the-bit configuration. The RSVD sensor is located 11.1 feet above the bit in the point-the-bit RSS. The real-time near-bit caliper is measured 8.2 feet above the bit. Optionally, a Pay-Zone Steering module is placed at the bit for inclination, RPM and Gamma Ray measurement.

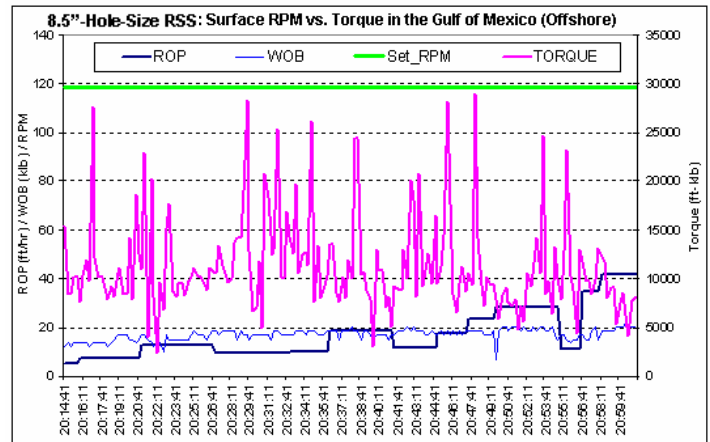


Figure 2. Surface parameters/data during downhole full-blown stick-slip. Notice that rotary torque fluctuation correlated highly with the downhole near-bit stick-slip data in the figure below while the WOB was kept nearly constant. The Set_RPM is the programmed surface RPM that is different from the actual surface RPM. It is noticed in the above figure that stick-slip tends to reduce ROP.

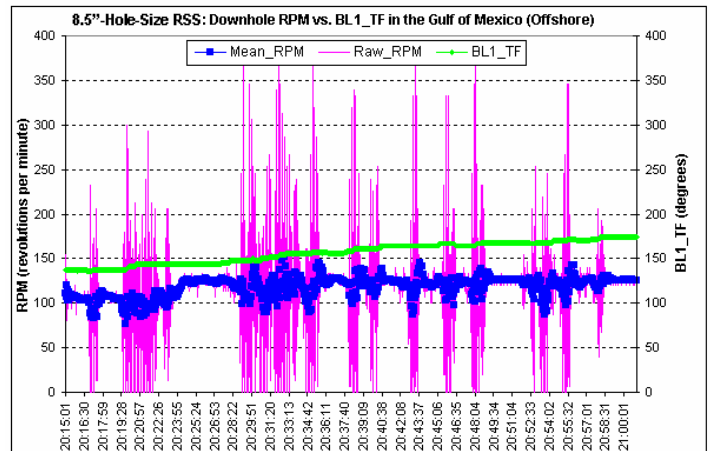


Figure 3. Downhole mean and raw RPM vs. blade housing toolface angle (BL1_TF). The slowly changing BL1_TF (140 ~ 170 degrees) indicates the non-rotating blade housing was substantially stationary, compared with the mean drillstring rotation (about 120 RPM). The raw RPM variations between 0 RPM and 380 RPM indicate the onset of a full-stall stick-slip. The corresponding Stick-slip Severity (SS%) in the period is approximately between 200% and 300%.

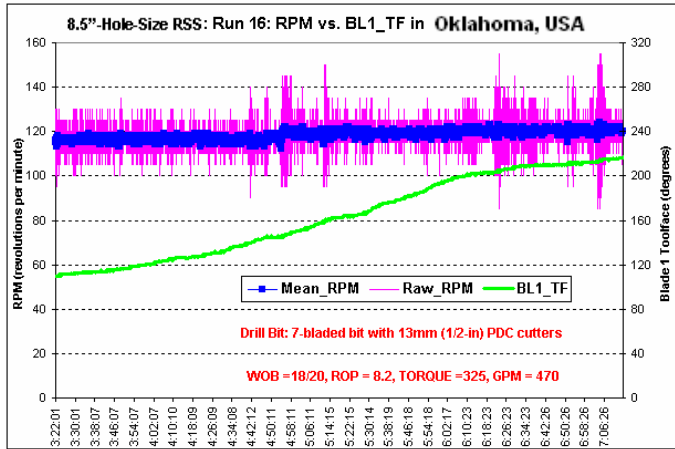


Figure 4. Low RPM variations with a 7-bladed bit with 13mm PDC cutters. The average ROP was reported as 8.2 ft/hr. The slowly changing BL1_TF (119 ~ 219 degrees) indicates the non-rotating blade housing was substantially stationary, compared with the mean drillstring rotation (about 120 RPM).

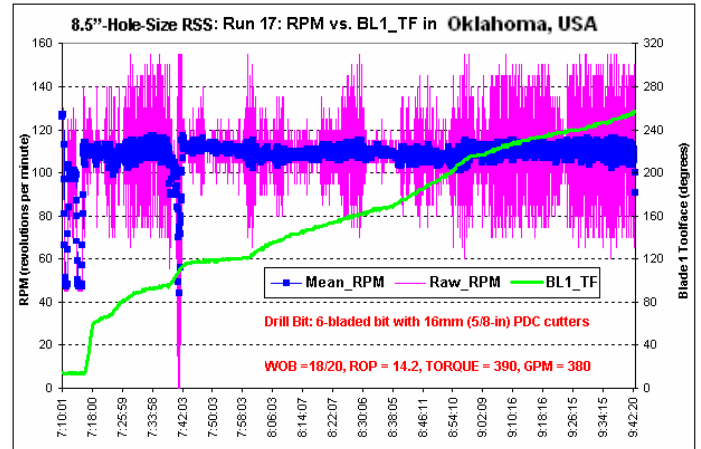


Figure 6. High RPM variations (Stick-Slip Severity $\approx 72\%$) with a 6-bladed bit with 16mm PDC cutters. The average ROP was reported as 14.2 ft/hr. The slowly changing BL1_TF (20 ~ 260 degrees) indicates the non-rotating blade housing was substantially stationary, compared with the mean drillstring rotation (about 115 RPM).



Figure 5. The less aggressive PDC bit used in the above run. This picture was taken after the above run.



Figure 7. The more aggressive PDC bit used in the above run. This picture was taken before the above run.

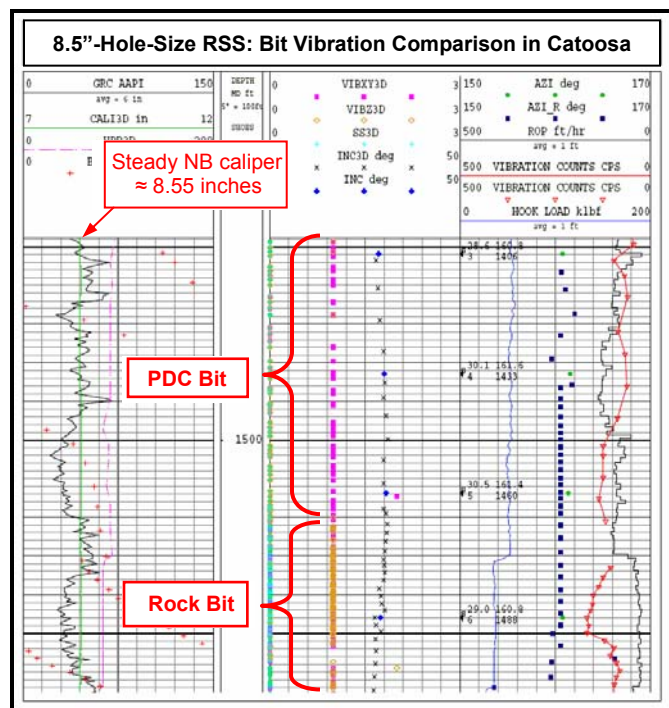


Figure 8. Vibration Comparison between PDC and Rock bit in the real-time MWD/RSS data. Lateral vibration (VIBXY3D = 1) was dominant while drilling with a PDC bit. In contrast, axial vibration (VIBZ3D = 1) was dominant with a rock bit.

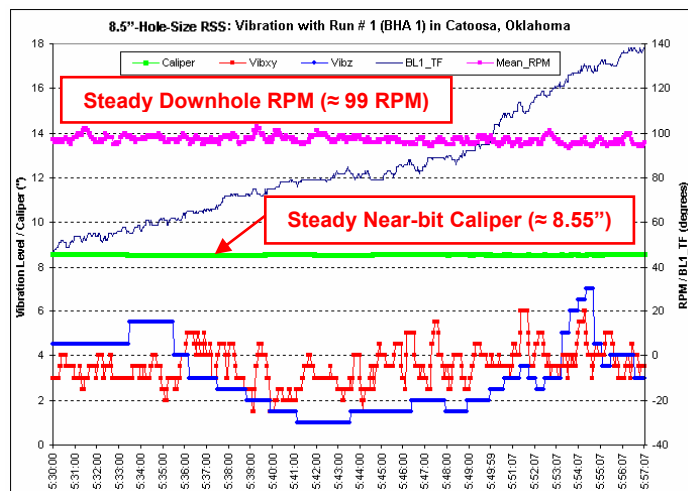


Figure 9. Relatively high lateral and axial vibrations (Vibxy and Vibz) measured in Run #1. The slowly changing BL1_TF (50 ~ 140 degrees) indicates the non-rotating blade housing was substantially stationary, compared with the mean drillstring rotation (about 99 RPM).

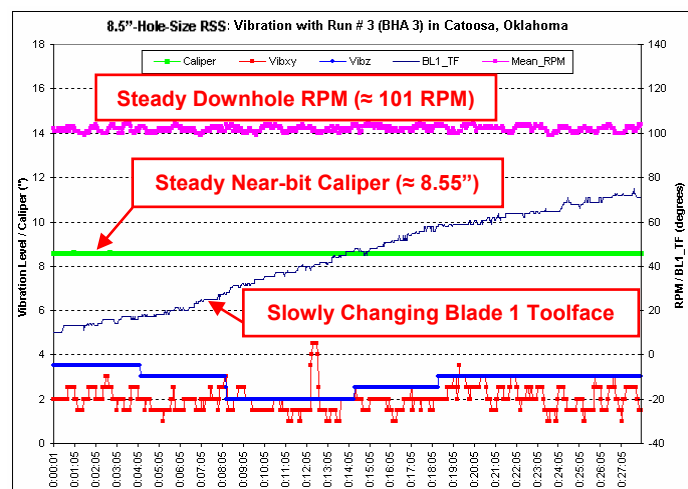


Figure 10. Lower lateral and axial vibrations (Vibxy and Vibz) measured in Run #3. The downhole near-bit vibrations were reduced by almost half from Run #1 after having changed the positions of drill collars and heavy-weight drill pipe in the BHA. The slowly changing BL1_TF (10 ~ 70 degrees) indicates the non-rotating blade housing was substantially stationary, compared with the mean drillstring rotation (about 101 RPM).

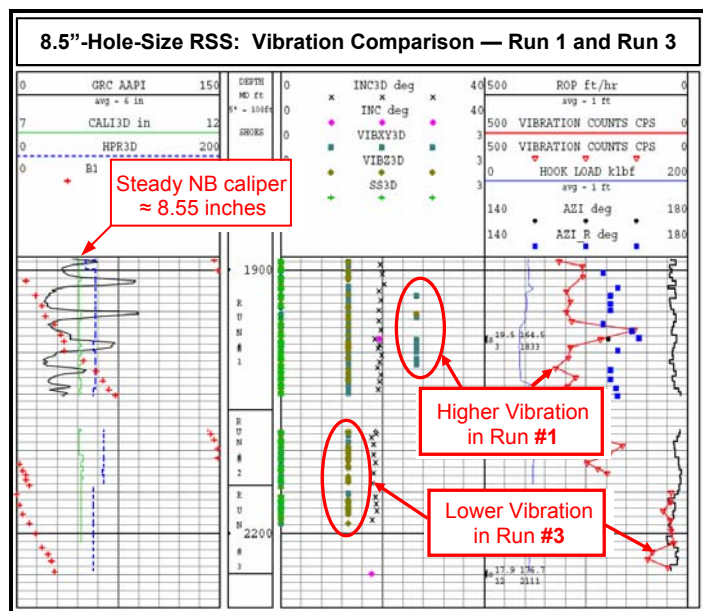


Figure 11. Vibration Comparison between Run #1 and Run #3 in the real-time MWD/RSS data. The RSVD lateral vibration (VIBXY3D) level went up to Level 2 and MWD vibration count was 300 CPS in Run #1. After having changed the positions of drill collars and heavy-weight drill pipe in the BHA, the lateral vibration level (VIBXY3D) became Level 1, and the MWD vibration count was reduced to 50 CPS.

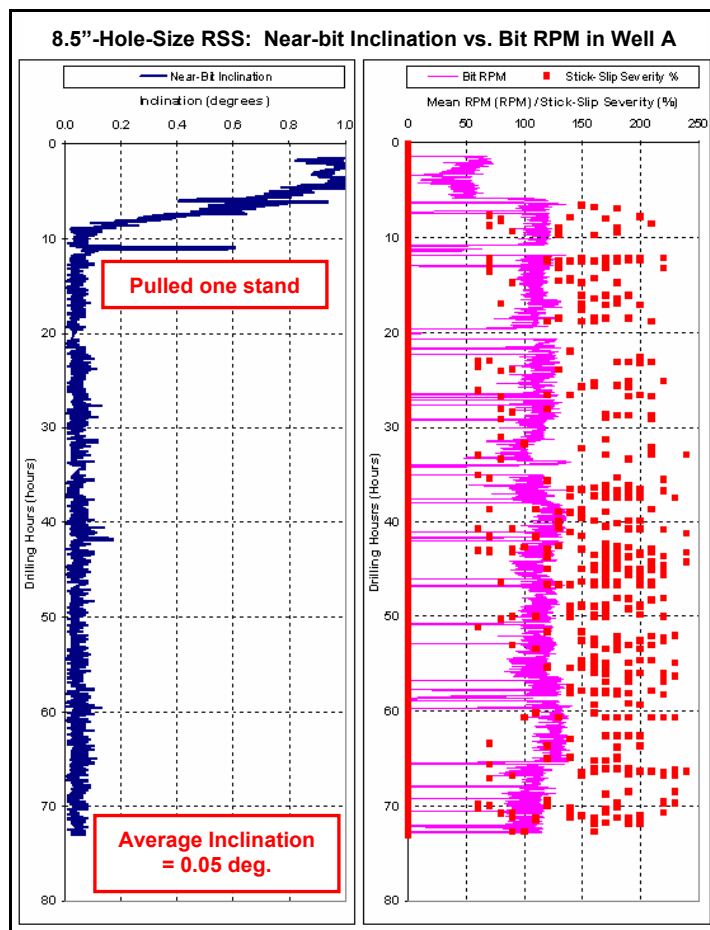


Figure 12. Near-bit Inclination, bit RPM and Stick-Slip Severity in % from Customer Well A. The fully automated RSS maintained excellent verticality for approximately 1,000 ft, while the excessive stick-slip problem hindered ROP. The average inclination of the near-vertical borehole is 0.05°, based upon the MWD static surveys.

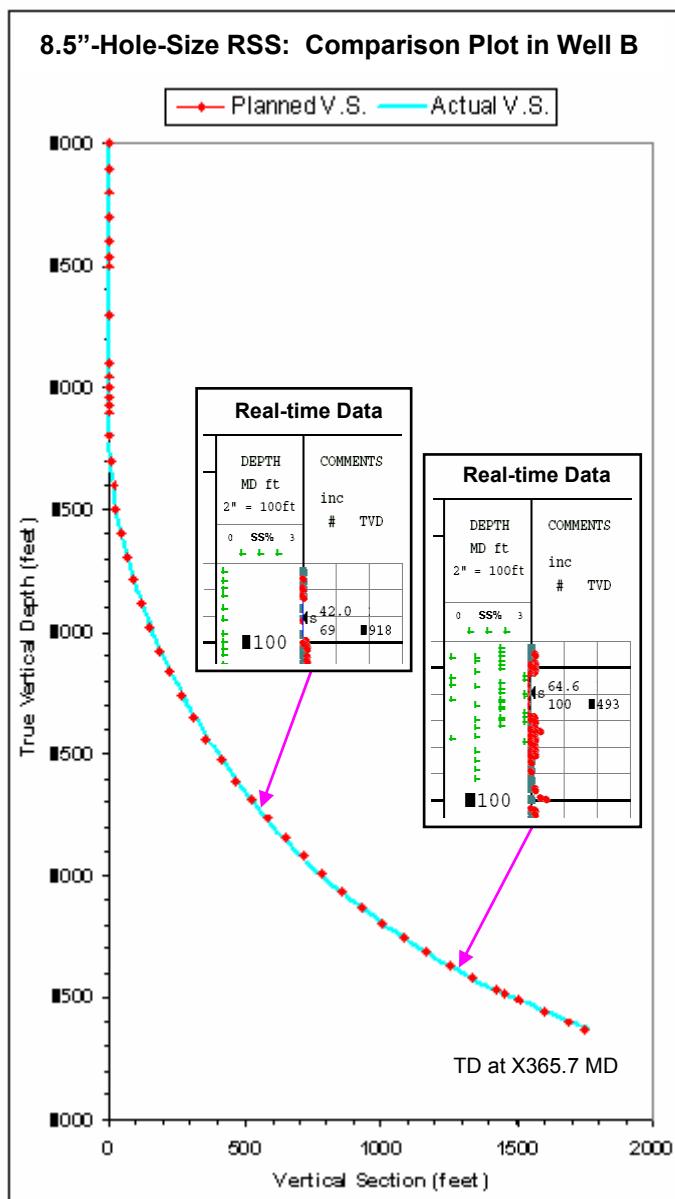


Figure 13. Comparison plot of Planned (red) versus Actual (blue) well path from Customer Well B. The RSS drilled 3,260 ft at an average ROP of 39.7 ft/hr without downhole failure. WOB was maintained at 15,000 to 20,000 lbs. The RSVD detected significant stick-slip in the second half of the well path up to the TD at X365.7 MD.

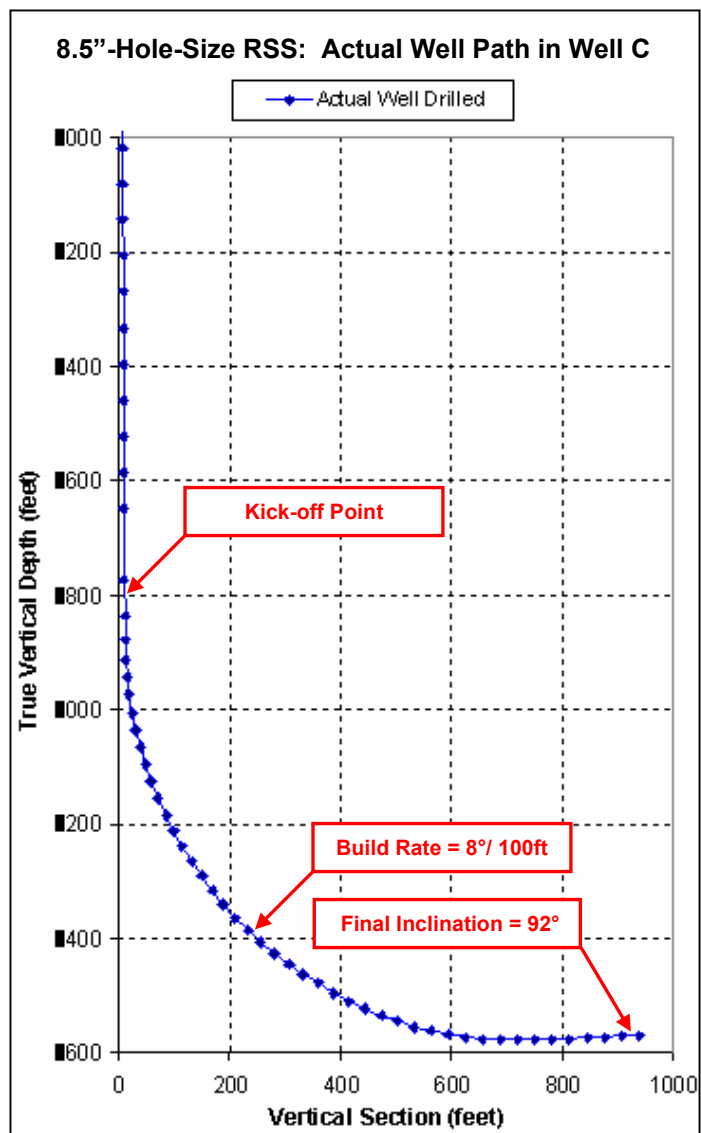


Figure 14. Actual well path drilled in Customer Well C. The RSS was used on the build section of a Fayette Shale well. The well plan called for 8°/ 100ft build rates to land in the reservoir at 92 degrees. Both stick-slip and vibration were low throughout the run as a result of using the motor-assisted RSS assembly. The assembly drilled 1,404 ft at an average ROP of 55 ft/hr.