



2009 NATIONAL TECHNICAL CONFERENCE & EXHIBITION,
NEW ORLEANS, LOUISIANA

AADE 2009NTCE-14-05

UNIQUE IMAGING TECHNIQUES OPTIMIZE PUSH-THE-BIT BOREHOLE QUALITY

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Abstract

Borehole quality of push-the-bit rotary steerable system (RSS) has not been extensively discussed in the past, partly because the polycrystalline diamond compact (PDC) bit gauge length and profile are directly related to the directional response of the tool, and different gauge lengths may be used based on the application. This type of system may lack lateral stabilization between the bit face and steering unit, depending on the type of bits used and the steering mechanism. To increase the lateral stability and borehole quality of the system, in-depth analysis of PDC bit and bottom-hole assembly (BHA) design is required.

This paper describes the results of extensive downhole drilling tests conducted on a push-the-bit RSS. The controlled tests were conducted using various PDC bits drilling through different formations. Improvements in stability and borehole quality have been examined using vibration data and a unique near-bit 2-D/3-D caliper image. Visualization of the borehole, using 3-D caliper images and their spectrum analysis, reveals that borehole quality is highly dependant on the BHA components below the RSS steering unit. The test results show that progressive testing with unique imaging techniques can systematically improve the performance of push-the-bit RSS and produce a better understanding of the interaction among a bit, formation, and RSS steering unit.

Introduction

Poor hole quality causes tight borehole, packing off, high torque/drag, stick-slip, degraded logging-while-drilling (LWD)/wireline log quality, unpredictable directional performance, and consequently problematic casing runs. There was initial recognition of the “crooked hole” problem in the early 1950’s. This “crooked hole” was repeatedly observed by drillers for decades in forms of “tight hole” and very high torque/drag even without aid of modern LWD tools. Advancement in LWD imaging technology can now allow engineers to identify 3-D borehole oscillation issues and oscillation frequencies while drilling.

Borehole oscillation

In 1951, MacDonald and Lubinski first expressed the precise definition of so-called “crooked hole” or “spiral hole” and provided a “crooked-hole” formula for the maximum drift size with a given bit and collar combination. Since their study (58 years ago), significant progress has been made in understanding the oscillating or cyclic nature of persistent borehole problems. Today it is known that the use of an extended-gauge polycrystalline diamond compact (PDC) bit can reduce borehole oscillations and improve borehole quality with specially designed steerable motors and particular point-the-bit RSSs.

Mechanical calipers obtained from wireline logs and acoustic standoff calipers from LWD logs have accelerated this understanding of borehole oscillation problems. The use of such equipment is no longer the only way to detect 3-D borehole problems, such as borehole oscillation.

Rotary Steerable Systems

A rotary steerable system (RSS) with a built-in mechanical caliper has been developed. This integrated mechanical caliper while drilling provides real-time and memory-based caliper images and has become a unique methodology of creating borehole caliper images, compared with conventional LWD acoustic standoff caliper images. Caliper image with the RSS is available in both point-the-bit and push-the-bit configurations.

These new 2-D/3-D near-bit caliper images are extensively used in the company’s research-and-development (R&D) department and helped quantify different drill-bit performances. The images are also used to improve the rotary-steerable BHA design for superior steerability, stability, drillability, controllability, and borehole quality.

The results from extensive drill bit and BHA research using the caliper images are also applied internationally during commercial runs to troubleshoot bit/BHA problems. Currently, the real-time and caliper images are available only to qualified R&D personnel for research purposes.

Integrated caliper imaging sensors

Integrating near-bit sensors with the RSS allows consistent measurement of borehole conditions, along with the three principal types of downhole vibration: torsional, lateral, and axial. Near-bit sensors also have been used to make comparative analyses of drill bit and BHA performance among different assemblies and wells.

The mechanical caliper image while drilling is now a standard, integrated component of all RSS and provides real-time and memory-based caliper images on all runs. The integrated mechanical caliper imaging has the following advantages:

- Caliper images are taken at the same position in a BHA (either point-the-bit or push-the-bit RSS);
- Real-time borehole image is available to R&D engineers for all the RSS runs;
- Integrated sensor does not add extra complexity to the RSS, which means the system delivers superior reliability;
- Integrated sensors are more economical and affordable than specialized subs;
- Sensor use is transparent to the RSS operator and requires no extra sensor/battery setup; and
- Unlike specialized subs, the sensors do not alter the BHA length or behavior.

Non-commercial field testing

In one case, real-time mechanical caliper images were used in extensive drill-bit testing for the push-the-bit RSS. Confidential drilling rig test facilities were used to conduct the controlled RSS directional test program: 1) the GTI Catoosa Test Facility near Tulsa, Oklahoma and 2) the Rocky Mountain Oilfield Test Center (RMOTC) near Casper, Wyoming. Both facilities provided adequate geological variations and rig/pump capabilities for the tests in 8 1/2-in. and 12 1/4-in. hole sizes. With no directional constraints at either of the facilities, they both offered a perfect test ground for controlled RSS testing.

Since 2007, the RSS in push-the-bit modes has been extensively tested with different drill bits at these test sites. An experimental 8-in. push-the-bit tool (for 12 ¼ in. hole size) shown in **Figure 1** was designed exclusively for this systematic testing. The main objective of the controlled tests was to establish the maximum dogleg using various bit gauge configurations and at the same time evaluate the system for stability, steerability, DLS consistency, and borehole quality. For all tests, similar surface parameters were used (WOB = 10 ~ 20 kbs, rotary speed = 110 ~ 120 RPM, and flow rate = 600 GPM). The RSS was set for 91% offset setting.

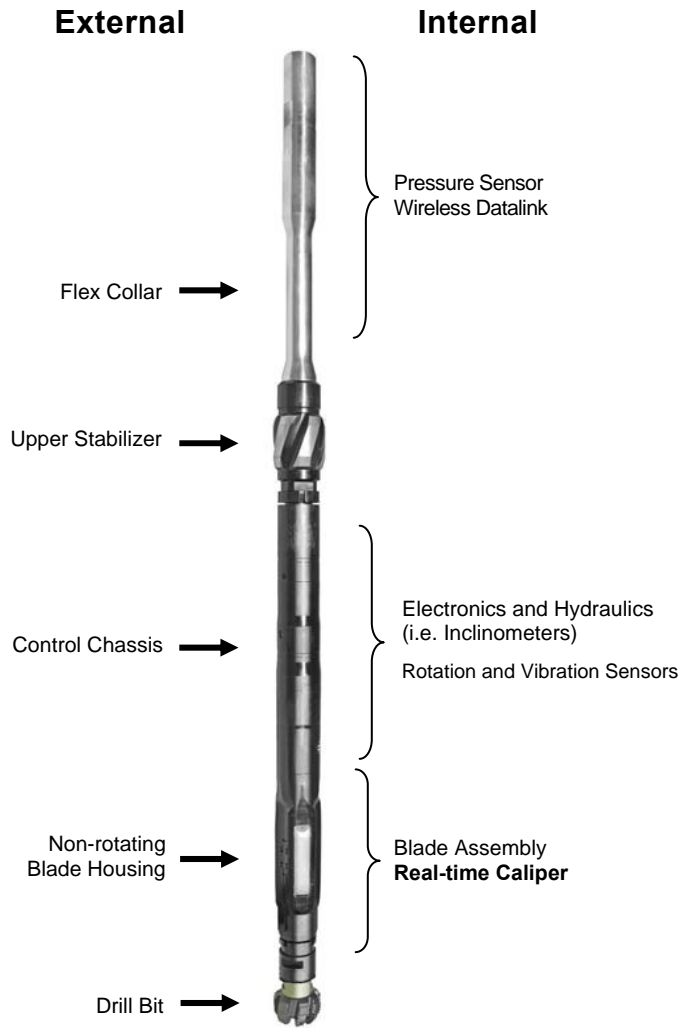


Figure 1: 12 ¼ in.-hole-size push-the-bit RSS

Real-time and memory-based vibration data and caliper images were used to evaluate bit/BHA performance. This analysis was used to understand whether the geometry and drill-bit changes influenced the RSS performance and resultant borehole quality.

Test Results

In this set of experiments, various polycrystalline diamond compact (PDC) bit gauge profiles were tested to evaluate hole quality and hence the knock-on effect of improved steerability and stability in a hard carbonate rock application (limestone). Four different PDC bits and one tricone (insert) bit were tested. The PDC bits tested were Tapered gauge, Tapered gauge with a ledge trimming sub, Short parallel passive gauge, and Long passive gauge with undercut.

The tapered gauge bit with a ledge trimmer created highest borehole quality, stability and toolface controllability. There were no signs of borehole ledging or spiraling in the 2-D and 3-D caliper images in both sandstone and limestone. Due to the added length with the ledge trimmer sub (about 1 ft), the maximum build rate was approximately 3.9°/100 ft in limestone. In all the tests conducted, the better quality borehole was always obtained with the use of a ledge trimmer. **Figure 2** shows the ledge trimmer sub used in this experiment.

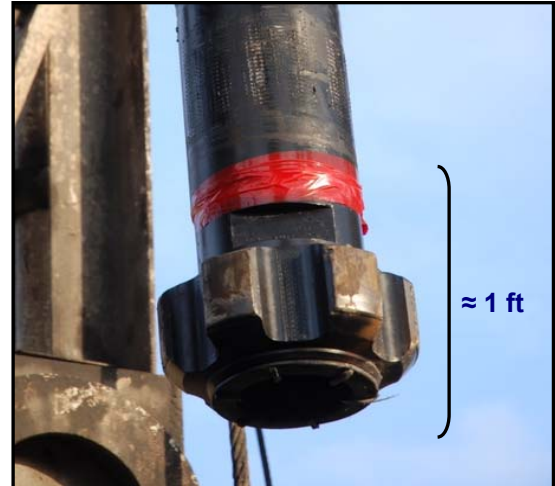


Figure 2: The experimental ledge trimmer sub

Among the different PDC bits without a ledge trimmer, the short parallel passive gauge bit shown in **Figure 3** produced the highest build rate, approximately 5.7°/100 ft in limestone. Further, this bit provided the best balance among steerability, lateral/axial stability, toolface controllability, and borehole quality.



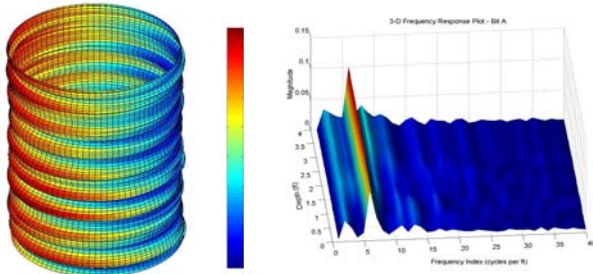
Figure 3: The short parallel passive gauge bit

Borehole Oscillation Observed

Obvious borehole oscillation problems were observed in 3-D mechanical caliper images and their frequency spectrum plots (as shown in **Figures 4a** and **4b**) from the tapered gauge bit and the tricone bit, running without a ledge trimmer.

In the 3-D images, borehole oscillation problems, ledges, and erratic borehole surfaces can be visually confirmed. In the figures, the right side of the image is highside of the borehole (gravity toolface = 0°) and the left side of the image is lowside of the borehole (gravity toolface = 180°).

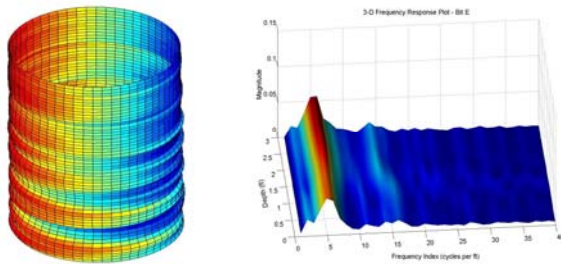
In the 3-D frequency spectrum plots, oscillation frequency, measured depth, and magnitude are shown in x, y, and z axes respectively. The height of the plot in the z-axis shows the magnitude of frequency response. Local minima and maxima are colored in blue and red respectively.



3-D Caliper Image:
Tapered gauge bit

Frequency Spectrum:
Tapered gauge bit

Figure 4a: The tapered gauge bit response



3-D Caliper Image:
Tricone bit

Frequency Spectrum:
Tricone bit

Figure 4b: The tricone bit response

Rotary-Steerable BHA Optimization

After the above bit gauge test, the 12 1/4-in.-hole-size push-the-bit RSS went through design changes to further shorten the distance from the bit to the steering unit as shown **Figures 5a** and **5b**. The objective of this change was to optimize the system to work with “off-the-shelf” passive gauge bits for superior steerability and borehole quality. Also, shortening the distance is thought to reduce the propensity for borehole spiraling that the previous test data suggested. A few months later, more testing was conducted with the short passive gauge bit shown in **Figure 3**.



Figure 5a: The “standard” push-the-bit RSS

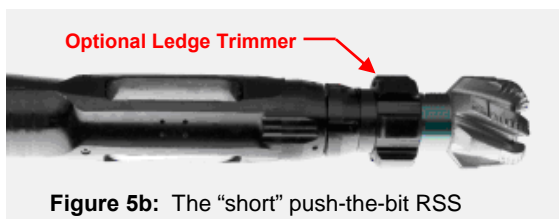


Figure 5b: The “short” push-the-bit RSS

In this test, the experimental “short” push-the-bit RSS shown in **Figure 5b** produced 6.5° – 7.0°/100 ft in limestone. This RSS exhibited not only high steerability but also excellent toolface controllability, predictable doglegs from 0° to 7.0°/100 ft in pure build, drop, turn, compound build & turn applications, and high-quality borehole. **Figure 6** shows the results of the pure build-up testing with and without a ledge trimmer. The data reveals that, up to 80% offset, the yielded build rates (up to 6.5 deg. per 100ft) are linearly proportional to the programmed offset. A red dotted line is added in **Figure 6** to show the linear region. Also, the use of a ledge trimmer did not affect the resultant build rate with this tool. The steering consistency of this experimental RSS was excellent.

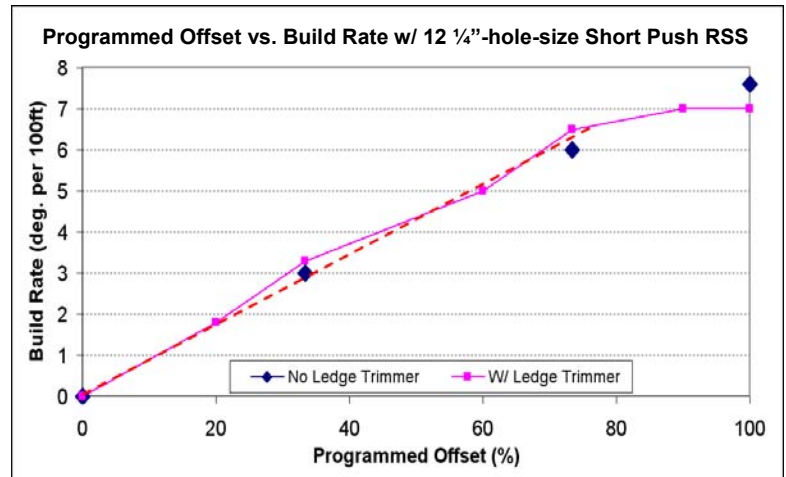


Figure 6: The pure build-up testing results

Mechanical Caliper Image

The borehole quality, analyzed with the 2-D and 3-D caliper images, was marginally better when running the bit with the ledge trimmer integrated to the RSS. **Figures 7a** and **7b** show 2-D/3-D caliper images, and **Figure 7c** shows their corresponding frequency spectrum plot. In this particular limestone section (drilled approximately 55 feet), the target toolface was set to highside (gravity toolface = 0°), and the target tool offset was set to 75%. The BHA yielded 6°/100ft build rate while producing high-quality borehole.

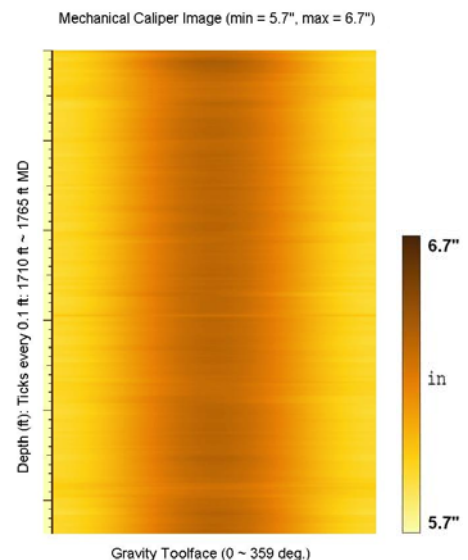


Figure 7a: 2-D caliper image – Short Push

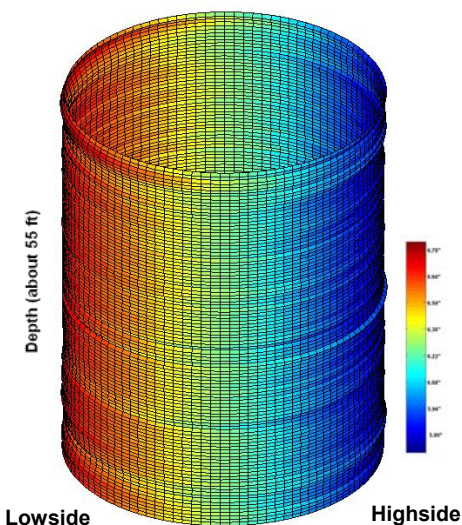


Figure 7b: 3-D caliper image – Short Push

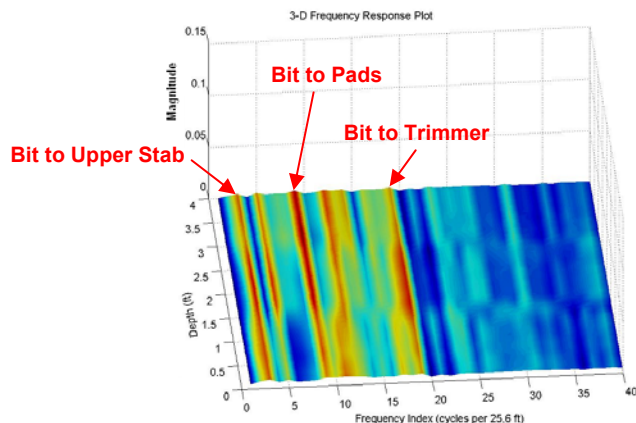


Figure 7c: Caliper frequency spectrum – Short Push

Frequency Analysis

The frequency spectrum of the caliper in **Figure 7c** shows that the peak of the frequency response is at the distance between the bit and pads, but other peaks are located at higher frequencies. These higher frequency components are induced by the different semi-contact points created by the parallel passive gauge bit. The period of the highest frequency response corresponds to the distance between the bit and the ledge trimming sub. The period of the strongest frequency response appears at the distance between the bit and pads.

It should be noted that the magnitude of all the oscillation frequencies is extremely small. The resultant borehole surface in **Figure 7b** is very smooth, and it exhibits high quality despite the high DLS that the BHA yielded. Generally, the higher the produced DLS, the lower the hole quality, with ledges and irregular borehole shapes in the case of steerable motors.

The spectrum data reveal that adding an undergauge ledge trimmer to the RSS between the bit and steering unit creates a new very-low-magnitude resonant frequency to the borehole caliper spectrum. Also, it suppresses the primary oscillation frequency response and provides significant borehole-quality improvement in problematic drilling conditions and formations.

Conclusion

A rotary-steerable system (RSS) with a built-in mechanical caliper has been developed. This integrated mechanical caliper, while drilling, provides real-time and memory-based caliper images to aid comparative analyses on different drill-bit performances and BHA designs.

During the extensive rotary-steerable testing, frequency analysis of the borehole caliper revealed that there are multiple borehole oscillation frequencies that correspond to the distance periods between a bit and other side contact points in the BHA. It is discovered that borehole quality can be dramatically improved by suppressing a peak frequency response of the borehole caliper.

The use of multi-dimensional caliper analysis resulted in the improved bit-gauge and BHA designs for superior balance among steerability, stability, steering consistency, and borehole quality.

Test results indicate that this unique mechanical caliper image helps engineers troubleshoot both bit and BHA problems. The effective use of caliper imaging leads to the early detection of borehole oscillation while the BHA is still in-hole and assists in optimizing bit and stabilizer selection for subsequent runs.

Acknowledgments

I would like to thank PathFinder Energy Services for its willingness to provide the data obtained with the 12 1/4-in.-hole-size PathMaker® RSS. I am grateful to PathFinder Energy Services for permitting the publication of this work. Special thanks to Steve Jones, Dan Taber, and other PathMaker Project members, for their valuable technical assistance.

Nomenclature

BHA	=	Bottom Hole Assembly
DLS	=	Dogleg Severity (degrees per 30 meters)
GPM	=	Gallons Per Minute
LWD	=	Logging While Drilling
MWD	=	Measurement While Drilling
NB	=	Near Bit
OD	=	Outer (or Outside) Diameter
PDC	=	Polycrystalline Diamond Compact
PDM	=	Positive Displacement Motor
ROP	=	Drilling Rate Of Penetration
RPM	=	Revolutions Per Minute
RSS	=	Rotary Steerable System
RSVD	=	Real-time Stick-slip and Vibration Detection
WOB	=	Weight On Bit

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Junichi Sugiura is an R&D Design Engineer with PathFinder Energy Services in Houston, Texas, USA. He holds a B.S. in Electrical Engineering Honors from the University of Texas at Austin in USA. In 1995, his career started as an Electrical Engineer in Japan. Joining PathFinder R&D in 2002, he has focused on developing sensor technology and downhole software algorithms for rotary-steerable systems. He is an author of several SPE, OTC, IADC, AADE, and SPWLA technical papers and holds several downhole-technology patents.

