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AN OPERATIONAL COMPARISON OF PUSH-THE-BIT ROTARY STEERABLE TOOLS

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October 2019

More than a dozen oilfield service companies design, operate, and/or sell rotary steerable systems, and the majority of these systems may be categorized as push-the-bit type systems. There is an appreciable range in the features and capabilities of these tool offerings, yet on a basic operational level most have much in common, yet there exist significant distinguishing differences. The purpose of this paper is to describe at this basic level both the primary operational differences and similarities of push-the-bit tools.

Introduction

Today's directional drillers have many choices in size, design, features and capabilities of rotary steerable tools. Tool sizes range from addressing borehole diameters greater than 17 ½" to those as small as 5 7/8". Features include a broad and often sophisticated offering of instrumentation and range of on-board sensors, including but not limited to high-precision six-axis accelerometer modules, near-bit inclination, natural and azimuthal gamma ray, multi-axis vibration, annular and bore pressures, magnetometers and gyrometers, mud resistivity and temperature, short range telemetry, and so on. Capabilities include impressive ranges in build rate, inclination and azimuth hold and adjustments to steering, fixed and proportional bias operation, high temperature and pressure operation, ranges in flow rate, styles of downlinking communications, integration with MWD/LWD strings, electrical power source, and so on.

There are two (2) prominent design classifications of these rotary steerable tools, being:

- Point-the-bit
- Push-the-bit

Point-the-bit rotary steerable tools employ various means to tilt the drill bit, producing an off-axis direction and side force for steering. A common means to achieve this is by bending of an internal drive shaft located within a non-rotating housing. Other means include creating and holding a tilt angle using a stationary unit housed within a rotating sub, and adjustable steering pads on a non-rotating housing. Examples of point-the-bit rotary steerable systems include Schlumberger PowerDrive Xceed, Halliburton GeoPilot (Jerez, 2014), Weatherford Revolution (weatherford.com), GyroData Wellguide (gyrodata.com), and the former Pathfinder Pathmaker (Sugiura, 2010).

Push-the-bit rotary steerable tools create a side force at the bit by means of extension of external steering pads against the borehole wall. The more common manifestation is the application of side force from steering pads positioned on a rotating housing; another embodiment applies the side force from a non-rotating housing. Examples of systems using steering pads on a rotating housing include many of the offerings within the Schlumberger PowerDrive family, such as Orbit (Al Mutawa, 2017), Weatherford Magnus (weatherford.com), Halliburton iCruise (halliburton.com), D-Tech RST (dtechdrilling.com), and APS RSS™ (aps-tech.com). Systems using steering pads on a non-rotating housing include BHGE AutoTrak (Kellas, 2005), Scout (scoutdownhole.com), and DoubleBarrel (doublebarrelrss.com).

As the rotary steerable service industry has matured, evolved, and responded to changes in market demands, more opportunities have been presented for push-the-bit designs than point-the-bit rotary steerable systems. This change has largely been created by the unconventional horizontal well market, which has driven a need for systems to be able to steer often complex and extended reach trajectories with increasingly greater reliability and consistency in performance and results. Some sources (Clegg, 2019) estimate that 72% of all wells today utilizing RSS use push-the-bit designs.

This paper describes two differing push-the-bit rotary steerable systems developed and marketed by APS Technology. The first system, manifested similar to conventional fully-rotating push-the-bit designs that may be operated either in rotary or motorized modes, is a 4 ¾" diameter RSS™ commercialized in 2018. The second system, a true rotary steerable push-the-bit motor (RSM®), relies on an integrated power section for its operation. Both systems will be discussed in technical detail, with both similarities and differences noted to other service companies' push-the-bit systems.

Distinguishing Between Differing Types of Push-the-Bit Rotary Steerable Systems

A primary difference between types of push-the-bit rotary steerable systems lies in whether the tool applies dynamic side force from a rotating housing, or a static side force from a non-rotating housing on the rotary steerable tool. If the tool has a rotating housing, it must be able to extend and retract its steering blades precisely and successively at required toolfaces to steer, and apply the required side force to the borehole wall, and perform these tasks repeatedly over a range of rotation speeds. If the push-the-bit tool has a non-rotating housing, it must extend its steering pads at precise vectors and independently vary the force applied by the steering pads.

Other primary differences in these systems include the type of fluid used to actuate the steering pads, if the tool may be motorized and whether a performance motor is required.

Brief Overview of the APS Technology SureSteer-RSS-475 Rotary Steerable Tool

The APS SureSteer™-RSS™-475 rotary steerable system is a "push the bit" rotary steerable tool integrated with an MWD directional, gamma, and vibration sensor tool. It may be configured and integrated with a suite of LWD tools via modular tool connections. **Figure 1** shows the basic system components.

The RSS™ steering head is also referred to as a bias unit or actuation housing, and is shown below in **Figure 2**. At the bottom of this steering head is an integral 3 ½ inch API Regular bit box that accommodates standard drill bits ranging in diameter from 5 7/8-inch (149.2 mm) to 6 ¾-inch (171.5 mm). Above the bit box, and located internally, is the oil compensation system for the main hydraulic system. Externally, the steering head/actuation housing also contains three (3) hydraulic steering blades, three (3) oil fill

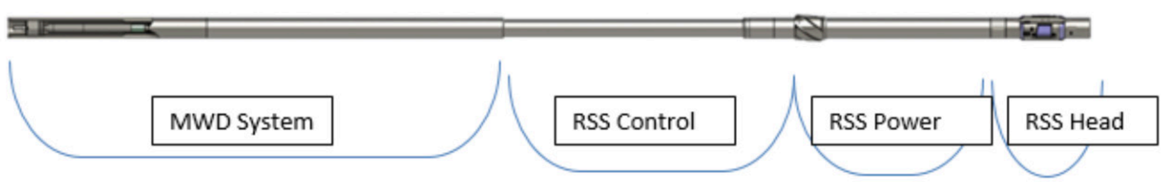

Figure 1. The Basic SureSteer-475-RSS System

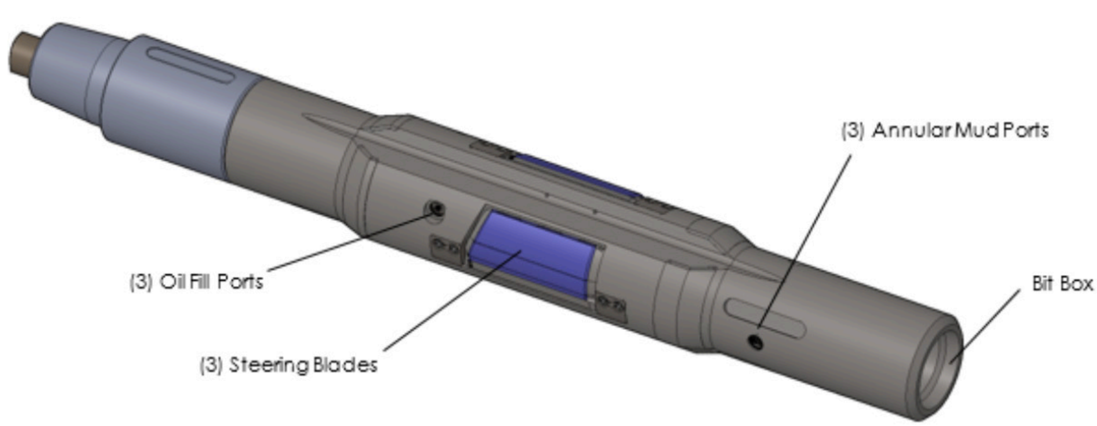

Figure 2. The SureSteer™-RSS™-475 Steering Head

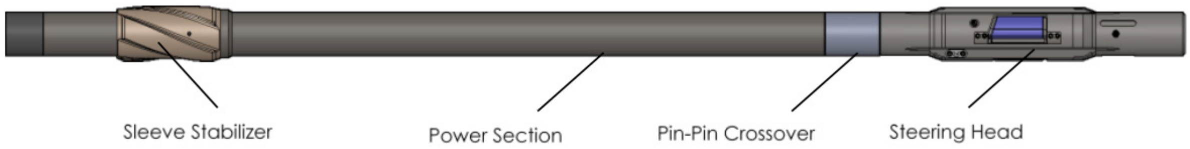

Figure 3. SureSteer™-RSS™-475 Steering Head, Power Section, and Sleeve Stabilizer

ports, and three (3) annular ports. These annular ports serve to prevent excessive pressure on the internal system in the case of a situation such as a plugged bit. Topping off the steering head is a NC38 pin-pin crossover sub that connects the steering head with the collar that goes over the RSS™ hydraulic system sonde. A centralizer resides within the pin-pin crossover sub, and it is this centralizer that ports hydraulic fluid from the uphole sonde to the steering pads in the actuation sub. The centralizer also channels mud flow from the annular area between the sonde and the bore of the collar to a gun-drilled passage co-axial with the steering head. Internal to the steering head/actuation housing are gun-drilled passages within the wall of the housing that carry hydraulic oil at pressure from the uphole manifold to the three sets of pistons that activate each steering blade.

Occupying the space immediately above the RSS™ steering head is the RSS™ power section. **Figure 3** shows the SureSteer steering head, its power section, and sleeve stabilizer. The power section contains an internal sonde in which is located a hydraulic manifold that houses five solenoid valves that set the system oil pressure and actuate the three steering pads. A hydraulic vane pump is located above the manifold and provides hydraulic power to actuate the steering pads. There is a hydraulic seal above the pump that separates the main hydraulic cavity from the turbine oil cavity. The hydraulic pump is powered by a five-stage mud flow turbine. This turbine also powers an alternator that supplies electrical power for the onboard electronics. There is a direct drive from the turbine, through the alternator, to the hydraulic pump.

A sleeve stabilizer is attached and resides on the collar at the location of the 5-stage turbine. An integral flex collar is located above the RSS™ power section and contains the control section. The flex section is designed to bend to achieve the required build rate capability in combination with the force provided by the steering pads, the location of the sleeve stabilizer, and the overall design of the bottomhole assembly. Within the power section's internal sonde are located two major electronic modules. A first module contains the rectifier and regulator electronics that converts the 3-phase AC voltages, delivered from the alternator, to a regulated DC voltage. The second module contains the control electronics and the biaxial magnetometer sensor for the tool. The control electronics contain the processor for the firmware that defines the tool operation. Also included in the control electronics are the driver circuits that control the solenoid valves located in the hydraulic manifold that actuate the steering pads.

The final section of the RSS™ steerable assembly is the MWD section. In the basic rotary steering configuration, the MWD section consists of the pulser, the pulser motion controller, MWD electronics, directional sensor, gamma sensor assembly, vibration sensors, and a single lithium battery backup power package.

Comparisons of Push-the-Bit Rotary Steerable Systems

In this section a range of features and capabilities of some of the current push-the-bit systems is reviewed. As mentioned earlier, current commercial push-the-bit rotary steerable tools include most of Schlumberger's PowerDrive tools, the relatively new Halliburton iCruise and Weatherford Magnus, Scout Downhole's Scout, and D-Tech's RST.

Two of the many commercial push-the-bit rotary steerable systems are primarily discussed herein, the motivating reason for their selection being the larger degree of availability of information in the public domain. Both the Schlumberger PowerDrive series of rotary steerable push-the-bit tools and the APS Technology SureSteer-RSS-475 push-the-bit tool achieve steering capability by generally similar means. One or more control valves connect the individual fluid inlet passages (leading to the steering pad pistons) to a source of high-pressure fluid as the steering unit rotates. This creates a modulation of pressure to each set of blade pistons in succession and in synchronization with rotation of the drill bit. This process causes each steering blade to extend outwardly from the steering unit, contacting the borehole wall at the same rotational position, resulting in pushing the bit and bottomhole assembly in the opposite direction. Differences in these two systems lie in:

- The source of directional data input for toolface control;
- The source of the pressurized fluid;
- The nature of the control valve(s);
- The nature and magnitude of the steering blade force;
- The means by which the desired blade extension position is achieved;
- The means to relieve pressure on the blade pistons;
- Downlinking.

Source of Directional Data Input and Toolface Control

The PowerDrive rotary steerable tools possess, among other sensors, an on-board directional sensor containing triaxial accelerometers and magnetometers, housed within a roll-stabilized platform, that is the primary source of directional data necessary for steering. While all other components of the PowerDrive rotate with the drillstring (or motor), the directional sensor may be completely isolated from this rotation. In the event of possible sensor failure, directional data may alternatively be sourced from the MWD directional tool.

The SureSteer™-RSS™-475 possesses an onboard biaxial magnetometer for measurement of steering head rotation speed and magnetic toolface, but otherwise receives full directional information from its direct connection to the MWD tool. Both the PowerDrive and the SureSteer tools are fully capable of finding their borehole orientation (e.g., borehole highside) from the directional data, and steering toward the desired direction by receiving a desired toolface (which may either be the toolface to steer towards, or the toolface to push from) either from a pre-programmed plan or an executed downlink.

For steering in a borehole with some inclination, the roll-stabilized platform of the PowerDrive steering tool rotates its upper pressure actuation disc valve to the stationary desired gravity toolface according to the direction in which the drill bit is to be steered. During rotation, the inlet opening to each steering blade rotates into alignment with the opening on the upper disc valve, and high-pressure fluid is introduced to the steering blade. The arcuate shape of the opening on the upper disc valve introduces the high-pressure fluid to the steering pad pistons, which in turn extends the steering pad. This extension, while centered on the desired toolface, begins some degrees prior to and ends some degrees after the actual desired toolface. When a new desired toolface is required, the roll-stabilized platform rotates the upper disc valve opening to a new, appropriate gravity toolface.

The SureSteer™-RSS™-475 uses inclination and gravity toolface from the MWD tool's directional sensor and magnetic toolface from its biaxial magnetometer rotation sensor for steering. With knowledge of borehole highside determined from static directional surveys, the dedicated solenoid valve controlling the flow of high-pressure hydraulic oil to the pistons of a steering blade is energized for opening at a magnetic toolface corrected for dwell angle, hydraulic system and rotation speed delays, such that the extension force is centered on the desired magnetic toolface from which to push. Fast sampling of the magnetometers provides resolution to both magnetic toolface measurements and determination of rotation speed. For Steering to drop, build or turn, the steering control firmware adds 180° and any desired toolface to the magnetic highside, such that the steering blade centered extension is opposite the desired steering direction. For Vertical Deviation Control, blade extension is centered on highside, such that blade force pushes the bit and drilling assembly to lowside.

Source of Hydraulic Activation of Steering Pads

Most commercial push-the-bit rotary steerable tools utilize the flow of drilling fluid in the bore of the drillstring to operate the steering blades. These systems generally divert upwards of 5% of the mud flow through an oriented (to the desired toolface), essentially stationary valve into (typically) three separate openings in a lower, rotating valve. It is through these openings that high-pressure drilling fluid is directed to each steering pad in succession. The opening, extending force of the steering pad is more or less a function of the differential pressure between the drillstring bore and the annulus. This may require planned selection of bit nozzle sizes to achieve a desired pressure differential, and means that steering force is not fixed and that there is, to a limited degree, a dependent relationship between bit hydraulics and rotary steerable tool steering force. Generally speaking, a desired relatively high side force requires a fairly large pressure drop. In some instances, chokes and similar restricting valves may be employed to provide a higher differential pressure. These systems that use drilling fluid as the source for generating the actuating force also require internal filter systems to prevent erosion and clogging of the pistons, which may become a reliability issue. The Schlumberger PowerDrive series of push-the-bit rotary steerable tools operates in this general manner.

Unlike most push-the-bit rotary steerable systems, the source of hydraulic power for the SureSteer™-RSS™-475 steering pad operation is a self-contained hydraulic oil system. This oil is pressurized, with flow driven by a positive displacement vane pump, and delivered to each steering pad via electrically-stimulated solenoid valves which are individually opened and closed by the control system. At normal and appropriate mud flow rates, a turbine alternator drives the vane pump, which in turn produces approximately 1000 psi discharge pressure to the multiple pistons that back each steering pad. An activation solenoid valve delivers this pressure to the pistons of each steering blade at a defined orientation (related to the steering control system and other parameters). At the completion of the steering pad extension, an offloader solenoid valve relieves the piston pressure, facilitating retraction of the steering blade. A fixed pushing force is exerted by each extended steering pad. This system defines a significant difference from those systems using mud hydraulics, where the force exerted by steering pads varies with the differential pressure between the bore and annulus.

For the PowerDrive push-the-bit tools, pressure is relieved from the steering pistons by the opening of a relief valve to the annulus. For the SureSteer™ tool, pressure is relieved from the steering pistons by the opening of an offloader valve to the low-pressure side of the hydraulic circuit.

Fixed and Variable Steering Pad Push Forces

Both the force and the timing of the extension of the steering pads energized by drilling fluid differential pressure are essentially fixed. In order to deliver the range of build rates demanded by the particular situation and objectives, tools using high-pressure drilling fluid are most often programmed to deploy their steering pads for a percentage of time. For example, such a push-the-bit tool may be programmed for both a steering ratio – a percentage of time wherein the pads are actively pushing against the formation – and a drill cycle time, which is estimated from a predicted achievable rate of penetration. Hence, some portion of this time is actively steered, with the high-pressure drilling fluid actuating the pistons that extend the steering pads. During the remaining time, if the tool is equipped with an auxiliary valve, flow of drilling fluid and high pressure is substantially reduced or entirely diverted from the steering pad pistons, such that the pads remain in the retracted position and the tool drills in a passive manner.

The SureSteer™-RSS™-475 steering control system provides for both fixed and variable (proportional) steering forces. The actual steering blade extension force is a product of the fixed pressure and the amount of time the steering blade is extended. The control system varies this blade extension time by controlling the dwell angle swept by the blade, where dwell angle ranges from 10 to 120 degrees. For a build or turn Steering situation, the SureSteer™-RSS™ may be programmed to constantly exert any constant dwell angle steering force, and in this sense the steering force is fixed in both force (blade pressure) and time (fixed dwell angle). But for autonomous steering control situations such as Vertical Deviation Control or Tangent Angle Hold control, the effective steering force is at a maximum 120° dwell angle when the difference between survey inclination and target or hold inclination exceeds a given limit. As the difference between these inclinations decreases, the control system autonomously reduces the dwell angle, eventually reaching either a minimum 0° dwell angle (for vertical control) or a 10° dwell angle (for tangent hold, where some constant force is required to work against the force of gravity). This defines a process of proportional steering force, which acts to reduce porpoising, overshooting, and wellbore tortuosity. While the force is fixed in terms of actuating pressure, it is variable over time (i.e., a variable dwell angle).

Operation in Non-Steering Mode

The two tools differ fundamentally in their operation in non-steering mode. To steer, the PowerDrive rotary steerable tool's roll-stabilized control unit sets the actuation system upper disc control valve to a stationary position according to the desired toolface for steering. During operation, some portion of the time (referred to as steering ratio) is spent with the valve set to this desired toolface. At the conclusion of this time, an auxiliary valve is rotated into position such that the flow of high-pressure fluid is blocked from all the steering blade pistons, and the steering tool acts in a non-steering (referred to as "straight") drilling mode for the remaining time. This control is modified by changing (downlinking) either or both the steering ratio and the rate of penetration index.

For the SureSteer™-RSS™, operation in non-steering ("disabled") mode requires a downlink to change the steering mode from that of Steering (or other) to that of Disabled. In Disabled mode the steering blade solenoid valves remain unenergized (closed), and no pressure is exerted on the steering blade pistons. Steering performance in Disabled mode tends to be stable, straight, and, except for unanticipated formation discontinuities, predictable.

Operation in Closed Loop Control Modes

For steering tangent sections, the PowerDrive rotary steerable push-the-bit tool may be downlinked to a "hold inclination-hold azimuth" closed loop control mode. In this mode, the tool receives continual inputs of inclination and azimuth from its roll stabilized directional control unit, and adjusts desired toolface on the fly to hold both inclination and azimuth.

Another example of closed loop control is the Schlumberger PowerV vertical drilling system, which autonomously uses on-board directional sensor data to find borehole highside, and direct the steering pads to extend at this toolface, thereby pushing the bit to a vertical orientation.

The SureSteer™-RSS™ also has two closed loop control modes: one for Tangent Angle Hold, the other for Vertical Deviation Control. For the former, the tool continuously monitors the difference between current survey inclination and hold inclination, and adjusts steering force (via changes to dwell angles). As the difference between survey and hold inclination decreases, so does dwell angle, and steering force is feathered. The frequency of adjustments is dependent upon the availability of survey inclination, which currently is either a static or non-rotational flowing survey. Plans exist to add azimuth control with the introduction of rotating azimuth and inclination measurements (currently being field tested in 2019).

The second SureSteer™-RSS™ closed loop control is that for Vertical Deviation Control steering. This is also a closed loop, autonomously operated steering, requiring no outside intervention. This control operates in the same manner as Tangent Angle Hold control, feathering dwell angle as the difference between the most recent inclination survey measurement and vertical decreases.

Steering in Rotary and Motorized Modes

Most commercial push-the-bit rotary steerable systems may be run in either rotary or motorized modes. While rotary operations may involve rotation speeds upwards of 200 rpm, limited to the range of the topdrive unit, motorized speeds may approach 400 rpm, where the top speed is a function of both the topdrive and the positive displacement motor. The rotary steerable tool must be able to actuate, extend and retract its steering blades at the desired toolface at the significantly higher rotation speeds applied by the combination of topdrive and motor operation.

A push-the-bit system exemplified by PowerDrive utilizes a disc-valve system connected to a roll-stabilized directional sensor platform, in conjunction with high-pressure drilling fluid, for actuation of its steering pads. During any one drillstring revolution, each of the three steering pads experiences an extension/retraction cycle. Owing to an arcuate design of the opening on the upper disc valve, in conjunction with the three circumferentially spaced circular openings on the bottom disc valve, each steering pad is opened and closed several degrees symmetrically about the desired rotational orientation. The actual number of leading and following degrees is a function of the angular arc described by the upper disc valve opening. It is possible, for instance, to begin opening of the next successive steering blade before entirely shutting off high pressure to the current steering blade.

As mentioned earlier, the SureSteer™-RSS™-475 tool utilizes configurable steering blade extension dwell angles. For a situation of a fixed 120° dwell angle at 100 rpm (equivalent to 0.60 seconds per revolution) drillstring rotation speed, each blade is actuated to the extended position for 0.20 seconds. Each of the three steering blades experiences an extension/retraction cycle once per revolution, such that there is 100% steering extension coverage. At 300 rpm rotation speed (0.20 seconds per revolution) and the same fixed 120° dwell, each blade is actuated to the extended position for 0.067 seconds. Each of the three steering blades experiences an extension/retraction cycle once per revolution, and again there is 100% steering extension coverage. Only one of the three steering blades experiences the extension/retraction cycle in a given timeframe, meaning following the first blade, the next blade in succession is not opened until the first blade is retracted. For a 120° dwell angle, a blade is opened 60° degrees before the actual desired toolface orientation, and is closed 60° thereafter. This same protocol is observed regardless of the magnitude of the dwell angle.

Both varieties of push-the-bit rotary steerable tools are capable of deploying steering blades once per revolution at rotational speeds in the 350-400 rpm range.

Correcting for Hydraulic System Delay

The steering blades of the SureSteer™-RSS™-475 tool utilize pressurized hydraulic oil for their actuation. Operation of each steering blade is controlled by a dedicated, direct-acting electromechanical solenoid valve. When opened, high pressure hydraulic oil is delivered to the pistons that extend a steering blade; when closed, pressure is lowered via routing of flow through a shared offloading solenoid valve. As with any solenoid valve, there exists a hydraulic delay associated with energizing and opening and closing the valve. If this hydraulic delay is not accommodated by the steering control firmware, then steering blades may be opened too late, resulting in error in the steering direction. Each SureSteer™-RSS™ tool is subjected to a calibration of its hydraulic circuit. The average solenoid energization time is 0.02 seconds. As a function of bias unit rotation speed, this translates into a variable blade delay in terms of toolface degrees.

The steering blade opening and closing control of the SureSteer™-RSS™ tool is based on magnetic toolface. Magnetic toolface is provided by a biaxial set of fluxgate magnetometers, which further function as a rotation speed sensor. By fast sampling determination of rotation speed, combined with a polynomial characterization of the hydraulic delay time, a blade angular delay (in degrees) and respective magnetic toolface is repeatedly computed and used to energize the steering blade solenoids. By this means, regardless of the drillstring rotation speed, the steering blades are opened (and closed) at their required magnetic toolfaces.

By way of example, the process of determining when to energize, open and close a steering blade solenoid valve may be demonstrated. The situation is one of Steering mode, where a desired target gravity toolface of 45° has been downlinked. An MWD directional survey indicates a gravity toolface of 10°, the RSS directional sensor measures a magnetic toolface of 150°, the current steering dwell angle is fixed at the maximum 120°, and when drilling commences the combined drillstring and motor rotation speed is 200 rpm. **Figure 4** is a steering rose diagram, showing gravity toolface (gtf, located in the outermost ring, in red font), and magnetic toolface (mtf, in the inner ring, in black font). Borehole highside is located at 140° mtf. The desired target of 45° is equivalent to 185° mtf, and therefore a steering blade must push from 5° mtf (indicated as A and by the large arrow). As the dwell angle is 120°, the blade must be extended at 305° mtf (B), and must be retracted at 65° mtf (C). Given a 200 rpm rotation speed and the characteristics of the solenoid and hydraulic system, the steering blade solenoid valve must be energized at 219° mtf (D) so that it is opened by point B.

Downlinking

Downlinking is the process of communicating to the downhole rotary steerable tool a command or a set of instructions and/or data, which upon receipt by the tool causes the tool to change a specific behavior. The most common means to downlink include pressure, mud flowrate, drillstring rotation speed, and in some fewer instances, electromagnetic telemetry. During the downlinking process, one or more of these parameters are caused to change in magnitude or time duration, and often in number. A downlink using pressure requires some sort of surface dump valve, manipulation of which causes negative pulses to be transmitted downhole, where they may be detected by a pressure transducer. Downlinking using manipulation of drilling fluid flowrate causes changes in downhole turbine rotation speeds, obviously necessitating the rotary steerable tool be equipped with a turbine/turbine alternator. While the primary equipment used for flowrate downlinking is the mud pump, a hydraulic bypass unit, plumbed into the drill rig's surface piping and controlled by the service company, defines less commonly used equipment. Finally, changes in rotary/topdrive drillstring rotation

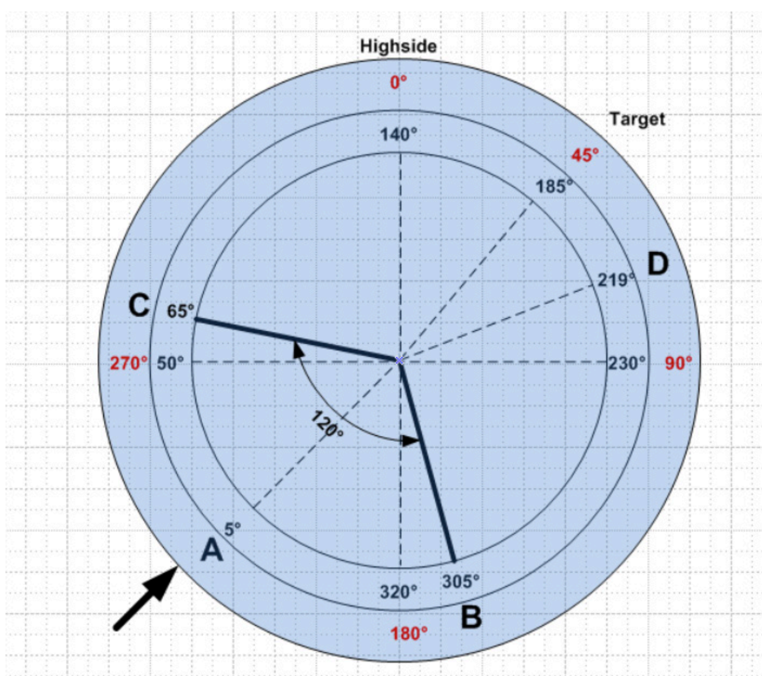

Figure 4. Steering Rose Diagram of Blade Actuation for 45°R Steering

speed are further used to convey downlinking instructions, requiring the downhole tool to possess a rotation sensor. The modulations of these parameters may be in both degree of magnitude and time. Combinations of the mechanisms – such as a downlink using both modulation of flowrate and rotary speed – are also employed.

Schlumberger's PowerDrive rotary steerable tools may use changes in mud flowrate as a standard downlink, or changes in rotation

speed as part of their QuikDownlink. Downlinks using flowrate may distinguish the instruction by using differing levels of pulse height and/or pulse width.

The content of PowerDrive downlinks includes instructions to:

- Increase or decrease desired toolface;
- Increase or decrease steering ratio;
- Increase or decrease rate of penetration index;
- Change the source of the control mode (i.e., directional sensor data);
- Instruct for inclination and azimuth hold operation;
- Contain data types and values for use in closed loop/feedback control operations.

The process of downlinking to APS Technology's SureSteer™ rotary steerable tools involves timed sequences of flowrate and rotation speed modulations, the combination of variables providing a higher degree of assurance of not being subject to a random set of conditions that may cause an inadvertent downlink. Most downlinks are conducted off bottom, generally immediately after acquiring flow-off static directional surveys, and may be conducted with the drillstring rotating, reciprocating, and in limited cases, while drilling. The content of the downlinks is limited to the mode of steering and changes to certain parameters within those modes. The modes are:

- Steering
- Tangent Angle Hold
- Vertical Deviation Control
- Disabled

Steering mode is used when it is desired to kick off from vertical, build, drop, turn the path of the borehole, or geosteer. The steering blade force may be set at any desired dwell angle from 10° to 120°, and at least two settings may be pre-programmed. Tangent Angle Hold mode places the steering control into an autonomous state that adjusts the steering angle (the toolface at which the steering blades are extended) and blade force based upon the difference between current survey inclination and the hold inclination. Survey inclination is sourced from static surveys (acquired either at connections or any time there is no drillstring rotation); and in the near-future, from rotating inclination measurements. Currently (2019) this mode does not hold azimuth (rotating azimuth measurements will be also be available in the near future), hence it is incumbent upon the user to perform a downlink to either turn left or turn right.

The Vertical Deviation Control mode is used when it is desirous for the rotary steerable tool to drop inclination and seek verticality. Like Tangent Angle Hold mode, Vertical Deviation Control mode is autonomous, and blade force is progressively reduced ("feathered") as the difference between current inclination and the vertical decreases. The Disabled mode prevents any blade extension, placing the steering tool into a passive state; this mode is useful for reaming, backreaming, drilling shoe tracks, and is also used in combination with Steering mode for geosteering operations. The minimum time it takes to perform these major mode downlinks varies with the mode, from almost 3 minutes to just over 4 minutes.

There also exist a few minor mode downlinks within these major steering modes, used for purposes such as to set desired toolface (magnetic or gravity), adjust for bit/bha walk, change blade dwell angle, and similar. These minor mode downlinks are abbreviated, not requiring a survey, and require relatively little time to perform, generally in the range of 2 to 5 minutes.

Figure 5 illustrates a typical SureSteer™ downlink, this particular example being a downlink to Steer mode, instructing for a 50° dwell angle and a target at 0° gravity toolface. The downlink commences with a no-flow connection MWD survey, after which flowrate is established and the RSS acquires its survey. There follows two dips in flowrate, which signify in this case Steer mode with a pre-programmed 50° dwell angle. The dips in flowrate must cross, for at least 10 seconds, a downlink detection threshold, which in this case has been fixed at 2000 rpm alternator speed. Following the dips, there occurs a period of at least 60 seconds of drillstring (or drillstring and motor) rotation, which must exceed a user-fixed threshold. At the conclusion of this rotation pulse, a confirmation of the downlink is transmitted to the surface, and the RSS™ tool is configured to steer to borehole highside. A short toolface setting downlink could immediately follow this downlink to set a desired toolface direction.

The APS SureSteer™-RSM® Push-the-Bit Rotary Steerable Motor

The APS SureSteer™-RSM®-675 was designed to provide all the advantages of a rotary steerable system and all the power of a performance drilling motor. The RSM® is unique among the offerings of commercial push-the-bit systems in that it consists of a steering head integrated with a positive displacement motor. The uniqueness lies in the RSM's internal driveshaft that directly connects with the transmission of the mud motor. The mud motor may be provided by the directional drilling company, may be any of a range from low to high speed for a specific application, and does not need to be of a high-performance nature. This integration decouples the rotation of the steering head from that of the bit, meaning, for example, that the motor may turn the bit at 160 rpm while the RSM steering head is turned at 80 rpm. This architecture yields significant benefits to drilling operations, lowering otherwise necessary high drillstring rotation speeds. This feature also allows all of the power of the motor to be delivered to and used by the bit, and not wasted turning a heavy steering head, as it is with most commercial push-the-bit systems.

Figure 6 shows a diagrammatic representation of the SureSteer™-RSM®-675 system.

In operation, all components of the RSM rotate, including its on-board directional sensor, which is located within four feet of the bit. This sensor is comprised of a triad of Q-Flex accelerometers and biaxial fluxgate magnetometers, making it independent of MWD sensor measurements while additionally enabling rotation and steering angle sensing. Toolface resolution, and consequently steering accuracy, is enhanced by the fact the steering housing may be rotated considerably slower than the bit.

In many respects, the SureSteer™-RSM®-675 shares much in common with its SureSteer™-RSS™-475 counterpart.

- The RSM®-675 also uses a hydraulic oil system in combination with a vane pump for the source of its high-pressure fluid for

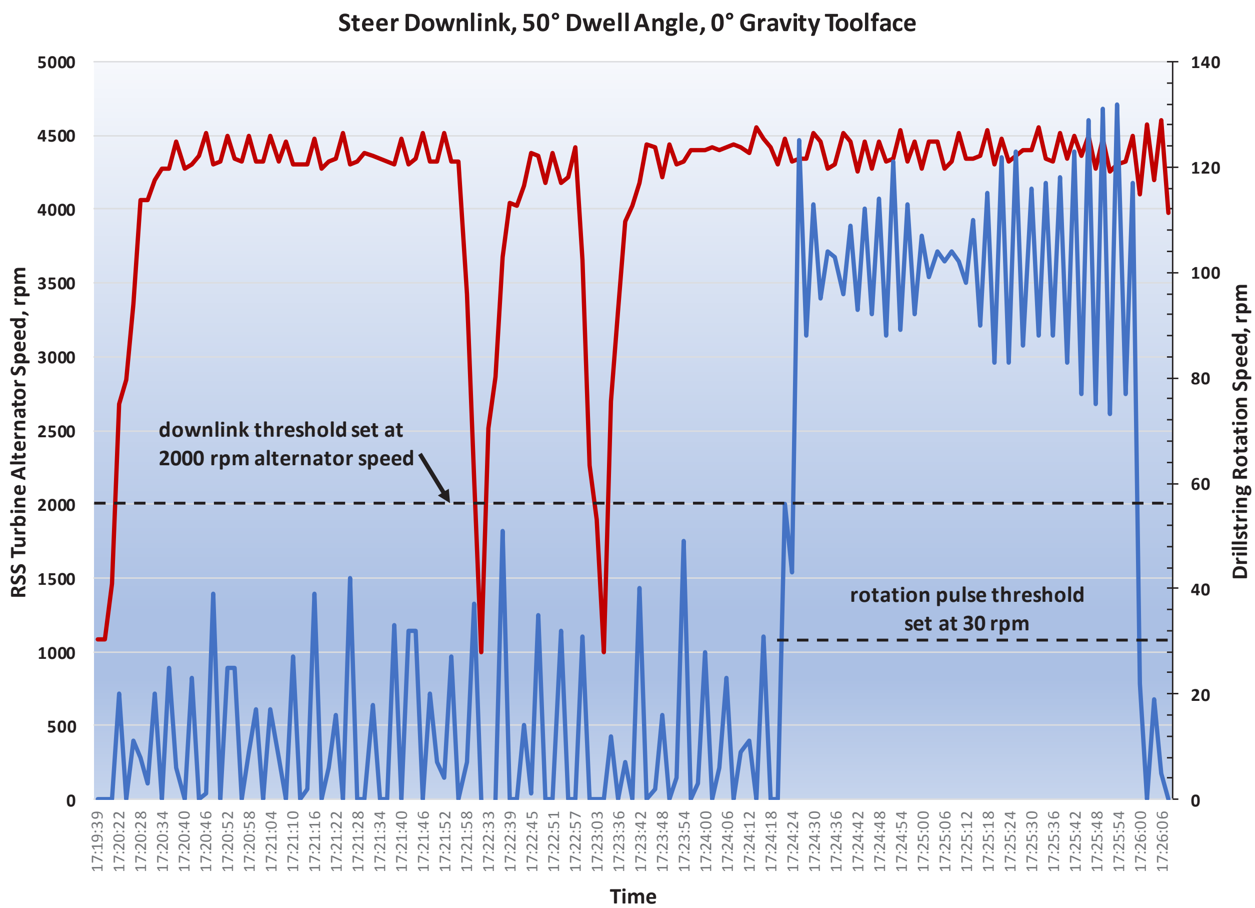

Figure 5. A SureSteer™ Steer Downlink

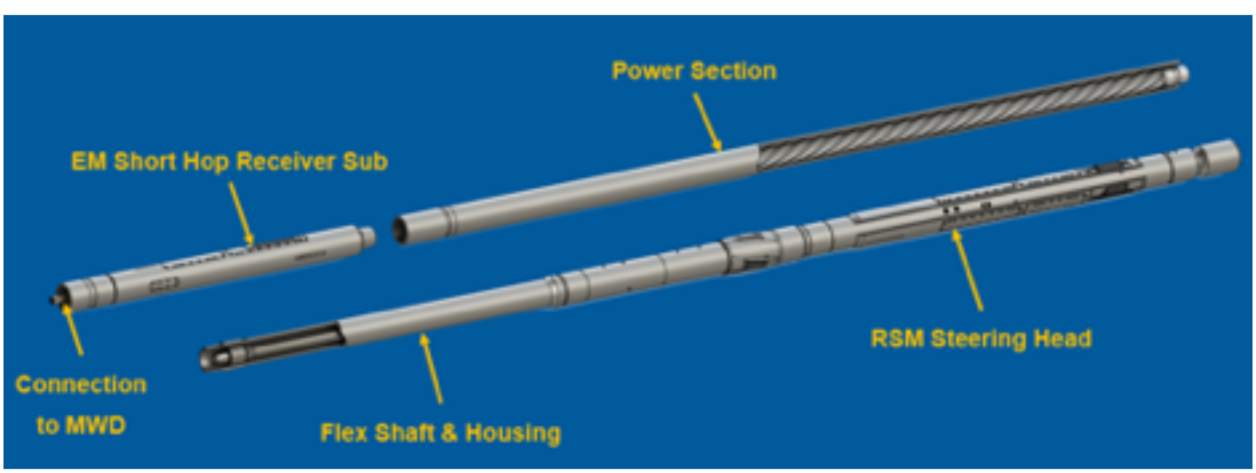

Figure 6. The SureSteer™-RSM®-675 Rotary Steerable Motor

actuating its three steering blades. Whereas the vane pump in the RSS™ turns at flowrate-generated turbine speeds (generally in the range of 2000 to 5000 rpm), the larger vane pump in the RSM® turns at the flowrate-generated speed of the power section, generally in the range of anywhere from 60 to 180 rpm. It, too, generates approximately 1000 psi for blade actuation, but against larger pistons.

- The RSM®-675 is equipped with a sleeve stabilizer located 10.8 feet from the bit (versus 9.3 feet for the RSS), and is most often operated with a flex collar at its top end.
- The downlinking to the RSM® is virtually identical to that of the RSS™, except instead of flowrate changes being proxied by turbine alternator speed, in the RSM® an alternator is driven by takeoff gears on the internal, motor-driven driveshaft.
- The RSM® houses its sensors and electronics in external body hatches, as opposed to internal sondes.
- Like the RSS™, the RSM® has a scribeline that is either aligned with or corrected for offset from the highside scribeline of the MWD directional sensor.

While some differences have been briefly noted, the major differences between the RSM® and the RSS™ include:

- The RSM®-675 incorporates an internal driveshaft that is directly connected to any appropriately sized power section.
- The RSM® steering head is rotated independently of the power section, and is entirely decoupled from the bit rotation speed.
- Operated by its integrated power section, the RSM® not only mitigates, but is largely insulated from, drillstring shocks and vibrations.
- The RSM® houses a triaxial accelerometer package and a biaxial magnetometer sensor, for independent directional measurements used for steering and rotation sensing.
- The inclination measurement of the RSM®-675 is truly near-bit, located less than four feet from the bit.
- The RSM® encompasses upper, mid-span, and lower sealed axial and thrust bearing packages.
- With a need to communicate near-bit sensor, downlink confirmations, and steering head diagnostics over an intervening power section, the RSM® is equipped with a magnetic short-range telemetry system, hopping these data 40 to 60 feet to an upper short-range telemetry receiver directly connected to an MWD tool.

In all other respects, the RSM®-675 shares all the same functionality as the RSS™-475, such as the same steering modes, the same operation at high rotary speeds, the same non-steering and closed-loop steering controls. And whereas the SureSteer™-RSS™-475 is used for boreholes ranging in diameter from 6.0 to 6.75 inch, the SureSteer™-RSM®-675 is used for 8.50 and 8.75 inch borehole sizes.

Motorized Rotary Steerable Systems

Most of today's rotary steerable systems were originally designed to be operated by the drilling rig's rotary table and/or topdrive unit. These tools utilized the rotational drive of the table or topdrive for their steering operations, which spanned a rotation range up to approximately 200 rpm. In the last fifteen years the unconventional shale drilling market has driven significantly increased horizontal well footage, and increasingly longer horizonal sections. But whether steered with steerable motor systems or rotary steerable tools, there comes a point when transfer of weight and torque to the bit no longer is effective, rate of penetration drops and drilling costs rise. In addition, more powerful (and costly) rigs and rig equipment become necessary to reach the longer distances. Turning the drillstring at the high speeds demanded by PDC bits results in high repair, maintenance and operating costs, all factors adverse to market economics.

In response to these technical and economic conditions, most providers of rotary steerable systems adapted their tools for operation with straight housing positive displacement motors, putting more horsepower downhole. This innovation mitigated operating costs, relieving rigs from the need for otherwise high drillstring rotation rates, enabled longer horizontal sections, and reduced drilling times, drillstring wear, and the frequency and occurrence of drillstring dysfunctions.

Not all rotary steerable tools can operate and steer accurately at the higher rotational speeds imposed by the combined topdrive and motor speeds. This is particularly crucial for fully rotating push-the-bit systems that normally deploy all three steering blades once per revolution.

While there are few published case histories of operation of rotary steerable systems in combination with a positive displacement motor (Kellas et. al, 2008; Ochoa et. al., 2009; Okafor 2011; Dutta, 2013; Jerez, 2014), the benefits have been well demonstrated: considerably higher rates of penetration, greater footage drilled per bottomhole assembly, higher displacements, and significantly reduced stick slip, shock and vibrations. The caveat for these improvements is the requirement of a powerful, and more costly, performance motor. Due to the size of the rotary steerable tool, only a portion of the available and expended horsepower and torque of the performance motor is actually available for the bit.

Of all of the motorized options available today, only the APS RSM® has a fully integrated motor, and one in which all the horsepower and torque generated by the motor is delivered to the sole use of the drill bit. The rotor and transmission sections of the power section are directly connected to an internal driveshaft located within the steering head. The drill bit is decoupled from drillstring rotation, enabling high bit speeds with low drillstring rotation speeds.

Motorized RSS and Short-Range Telemetry

Whenever a rotary steerable system is operated below a motor, there comes a requirement to pass sensor and diagnostic data originating at the rotary steerable tool across the motor to an MWD tool. The communications channel may either be wired or wireless. Of the former, BHGE's AutoTrak (Kellas, 2005) offers a wired connection, facilitated by the fact this major service company provides all the customized equipment (e.g., motor, top sub, stabilizers) required to connect the steering head with the MWD tool. Halliburton's GeoPilot (a point-the-bit system; Jerez, 2014) also makes use of a customized wired connection in what the company terms "through motor telemetry".

Wireless short hop options entail either electromagnetic (EM) or acoustic short-range telemetry, wherein data are transmitted through formation, fluid or pipe channels. Regarding EM telemetry, transmission may use either the electric spectrum or the magnetic spectrum.

It is here – the means to wirelessly communicate across the motor - where both major service companies and other vendors of rotary steerable tools seldom have ventured to discuss. A search failed to find any published technical papers on the subject of wireless short hop telemetry used with motorized rotary steerable tools.

APS Technology has developed and field tested a wireless short-range telemetry communications system that utilizes the magnetic spectrum. The system consists of a solenoid-shaped, wire-wrapped, ferrite core transmitting antenna located within a wall hatch of the RSM®, and a similar receiving antenna located within a short sub connected to the MWD tool. Sensor and diagnostic data and downlink acknowledgements are communicated over a separation distance up to approximately sixty feet. The system uses a modulo-five frequency keying transmission scheme, including a separator symbol, and transmitting 20 bits per second at a central frequency of 2850 Hz. This scheme facilitates quick recovery from any garbled transmission. A first-generation iteration of this system, tested in 2013-2014 at a much lower frequency bandwidth, had problematic results at high flow rates, partially attributed to motor-induced vibrations, but more so to inadequate electronics and signal processing. This first-generation magnetic short hop system was strictly half-duplex communications.

The new generation system has very significantly improved performance metrics with considerably lower bit error rates. The improvements have been achieved primarily by addressing the receiver antenna and its electronics, which have been significantly upgraded by reducing active IC components and introduction of very high quality analog-to-digital and digital signal processing chips.

While the current generation of RSM® supports only a single dual transmitting/receiving antenna, this new generation magnetic short hop telemetry system incorporates multiple antennas that may serve dedicated functioning for transmitting and receiving (**Figure 7**). The upper sub connected to the MWD collar features a circumferential receiving antenna and a solenoid-shaped transmitting (or redundant receiving) antenna.

Summary and Conclusions

APS Technology has designed, developed and commercialized two push-the-bit rotary steerable systems. One system, the RSS™, shares a greater affinity to most current commercial systems in that it is fully rotating and may be operated in either rotary or motorized modes. The RSS™ is presently available in a 4 ¾" diameter, appropriate for borehole sizes ranging from 5.875" to 6.75". A 6 ¾" RSS™, equipped with near-bit azimuthal gamma sensors, will be available in early 2020.

The RSM® system is unique among the many commercial offerings in that it incorporates a positive displacement motor, and its steering platform is fully decoupled from bit speed, enabling high bit speeds for PDC bit drilling while providing fine toolface resolution for precision steering. This tool operates independently of MWD systems, and communicates with them via magnetic short-range telemetry. The RSM® is available in a 6 ¾" size for 8.5" and 8.75" boreholes; a 9 ½" RSM® (for 12 ¼" and larger boreholes) with near-bit inclination, natural gamma ray and mud resistivity sensors, will also be available in early 2020.

Unlike most push-the-bit rotary steerable tools, the RSS™ and RSM® use an internal vane pump to generate pressurized hydraulic

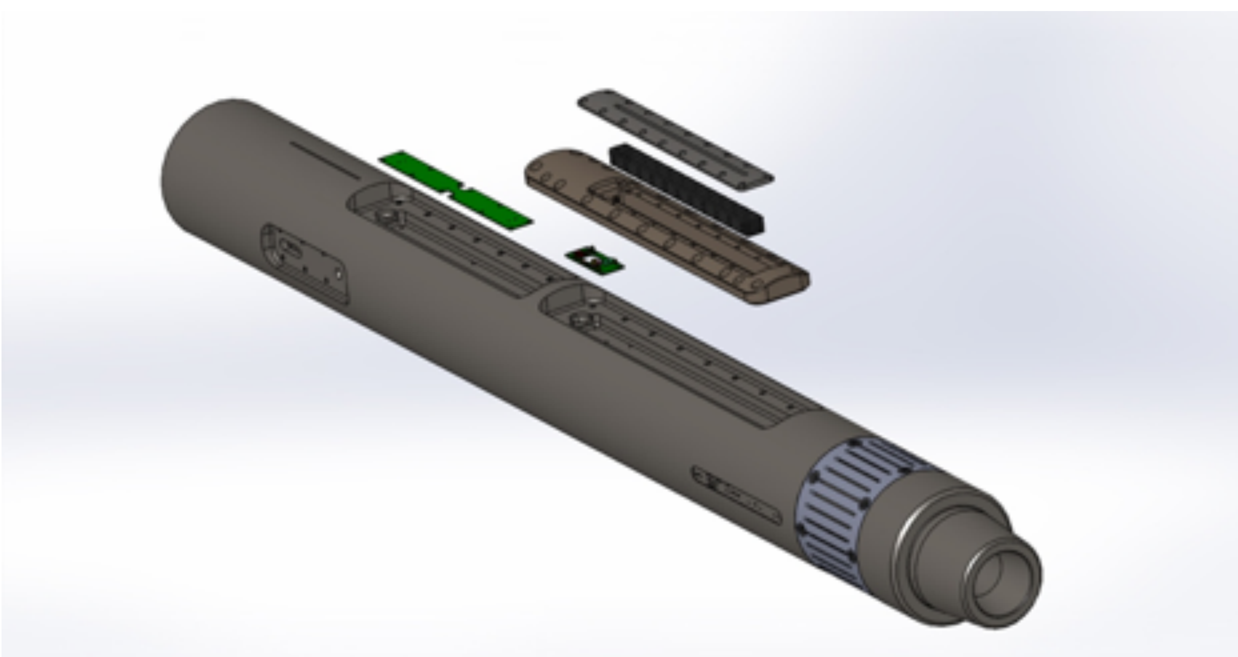

Figure 7. A Dual Dedicated Transmitter/Receiver Short-Range Telemetry Sub

oil for steering blade actuation. The resulting side force is a fixed constant of substantial magnitude, but with a design architecture of variable blade dwell angle extension, the forces delivered against the borehole wall possess and produce a proportional steering control that results in very low borehole tortuosity. This design philosophy means these systems are operated with no constraints on borehole hydraulics programs; drilling fluid in-bore filters are not required; and the pistons of the steering blades are not susceptible to abrasive wear.

Neither of these tools are reliant on batteries for operation. The RSS™ uses a turbine-alternator and the RSM® uses a rotor-driven alternator for the provision of electrical power for operation of the steering controls and the on-board sensors.

Control communications with the RSS™ and RSM® are achieved by relatively short-duration (← 5 minutes) downlinks using either the mud pump or a hydraulic by-pass unit to effect changes in flowrate, and the topdrive to produce a rotation pulse. Downlink confirmations (and diagnostics) from the RSS™ are delivered by its full integration with the MWD tool string, and from the RSM® via its short hop link to the MWD tool. Steering choices include active directional driller participation (e.g, build, drop, turn), passive, and the completely autonomous tangent angle hold and vertical deviation control options. **APS**

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ABOUT APS TECHNOLOGY

APS Technology, Inc. is a leading provider of Measurement While Drilling (MWD); Logging While Drilling (LWD); Rotary Steerable Systems (RSS); Drilling Systems and Drilling Optimization and Vibration Management products for oil and gas drilling. APS has deep engineering expertise in the design, development and manufacture of oilfield electronic, mechanical, instrumentation, sensor and software products; shock and vibration isolation designs; stress analysis for static and rotating conditions; and mechanical and electronics analysis for harsh environments. APS's customers include all of the major integrated multinational oilfield service companies, service divisions of national oil companies, independent directional drilling companies, MWD service companies and oilfield companies engaged in non-drilling related services. APS also provides product development services and proprietary products to customers worldwide. Visit https://www.aps-tech.com/ for more information.

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