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What is Wrong with my Drilling Data? Current State and Developments of Downhole Dynamics Measurement Tools

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Abstract

As information from downhole sensors plays an increasingly important role in drilling performance optimization and automation, trust in sensors and measurements needs to be established. The drilling industry is just beginning to consider sensor calibration critical to job execution for surface measurements. For downhole measurements, this work presents both a case for action and applicable solutions by addressing insufficient downhole data quality though analysis of the measurement tool design process.

Downhole measurements obtained during drilling are influenced by the entire drilling system, including reservoir aspects and downhole conditions, operational logistics and constraints, and data transmission and integration considerations. Critical aspects of sensor design, like power consumption, pressure and temperature ratings, measurement redundancies, data-processing technologies, and lifetime and cost-efficiency considerations, must consider these factors. Additionally, field calibration of downhole sensors, though tackled with multiple methodologies, remains an unsolved problem. A long-term process of improvement over several iterations of hardware design is contrasted with a more agile process of software development and deployment.

When analyzing data from downhole sensors, one will inevitably find a variety of known and unknown errors in a data set. Bad-quality data can originate from any process in the data supply chain, which includes sensor technology, tool design and manufacturing, tool deployment, and data collection, processing, and transfer.

This paper offers insights into sensor selection, tool design, and calibration, and lists the main constraints that need to be considered for each process. High-pressure, high-temperature, and high-acceleration downhole conditions may stretch sensors to their limits and make them unusable or error-prone. The main sources of errors, their characteristics, and mitigation methods are outlined. Tool life and calibration are essential during operations, and this work describes how such factors must be accounted for in the design process. Finally, data-processing techniques are described that potentially change the resulting data. These insights establish the relationship between sensor selection and calibration and good downhole measurement to improve drilling performance.

Introduction

Triggered through the shale gas boom in the US, the industry managed to significantly reduce drilling time and costs over the past years. The EIA Drilling Productivity Report shows that the productivity per rig in the Bakken region is 8 times higher in 2017 than it was in 2007 for oil and more than 15 times higher for natural gas[1]. Other US regions experienced similar productivity increases.

A large portion of the productivity increase has been achieved by horizontal wells, fracking, and hitting the right target zones[2]. However, part of this success can be attributed to improvements in both surface and downhole measurements during drilling[3]. Data collection was ultimately leading to increases in the rate of penetration (ROP), longer tool life, reduced nonproductive time (NPT), and faster learning curves of crews, among other benefits. Such applications have also sparked operators' interest in data collection during the drilling process. Drilling engineers are beginning to analyze such data streams on a regular basis, hoping to optimize drilling parameters and bottomhole assembly (BHA) designs. For example, downhole shock and vibration data has traditionally been collected to monitor and predict the life of downhole tools. Now similar data is used for insights into downhole forces and motions, which are critical to drilling performance.

In addition, drilling automation initiatives of particular drilling tasks and even the entire drilling process are on the verge of being commercially implemented. For any automated control efforts, reliable sensors are mandatory. Data is the bloodstream of an automated rig, without which drilling automation is unthinkable.

Together with increased awareness of the value of data came an increased awareness of the quality of the data. The problems with data were both organizational and technical. Any engineer who went through the exercise of collecting, merging, cleaning, and analyzing rig data from a variety of sources will agree that the drilling industry does not have a "big data problem" but a "messy data problem." In addition to data structure and transfer, data accuracy and precision are far from perfect. Recently, special initiatives have been formed to address issues specific to data quality. The SPE Drilling Systems Automation Technical Session (DSATS) Data Quality Subcommittee tries to foster industry and academic collaboration. Another initiative, the operators' group for data quality, consists of more than 20 operators that joined forces to promote standards that enable optimization and advanced analytics[4]. The operators' group recognized that advances in data quality start early in the supply chain—with the manufacturers of sensors and tools—and is working on standardized calibration devices and procedures for surface data[4].

Similarly, for downhole dynamics, the process of data creation and collection spans all areas from sensor selection and manufacturing, tool design, testing and calibration, deployment, data processing, and data analysis. Improvement of technical data quality needs to start at the very beginning of this supply chain. Therefore, the goal of this work is to raise awareness about sources of data errors that have their roots in the nature of sensors or throughout the deployment process.

Industry Oversight of Drilling Measurement

Downhole tools can be grouped into two categories—mechanical tools and electronic tools—and this paper will focus on the latter. Electronic downhole tools were first successfully deployed in the 1960s and 70s and have since played an increasingly important role in developing an understanding of downhole dynamics. Without such tools, it was quite difficult to drill and place wells efficiently, stay in the target zone, minimize drilling risk, avoid geohazard regions, or bypass subsurface regions occupied by other lease owners. The most common categories of electronic downhole tools are:

- Measurement-while-drilling (MWD) tools are mostly used to provide inclination and azimuth data from which the well path can be inferred.
- Logging-while-drilling (LWD) tools provide information on rock and formation fluid properties.
- Rotary steerable systems (RSS) provide downhole steering mechanisms for directional drilling, replacing conventional mud motors.
- Drilling dynamics measurement tools are probe- or collar-based tools that house sensors for operations-related measurements such as downhole weight on bit (WOB) and downhole torque.

These tools can be placed at different locations along the drillstring. For well-positioning (MWD) and well-logging (LWD) purposes, certain conventions and standards on measurements have been implemented over the years. Incorrect well position information can result in collisions with other wells or missing a target zone. These obvious downsides of dynamics measurement tools have led to the formation of industry bodies, including the Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA), as well as the Society of Petroleum Engineers – Well Positioning Technical Session. Over the years, these initiatives have improved and standardized measurements and data formats, and thus have improved the value of information from these sensors. Of course, standards and conventions need to be up to date with new developments and should be flexible enough to facilitate technological progress.

The drilling industry should also learn from the petrophysicists approach that knowing about data is just as important as knowing about the tools and processes with which the data was collected. Courses on petrophysics and log analysis include in-depth knowledge of a tool's working principles, deployment methods, and data processing.

If the oil and gas industry wants drilling automation to succeed, the same standardization needs to be implemented for downhole dynamic measurement, and the same awareness of a supply chain for data needs to be created among all parties involved.

Sensor Selection and Design

Sensor selection and design is governed by a variety of factors that impose technical limits. The availability of power, tool size, software, and calibration are important considerations for selection, design, and calibration of downhole sensors and will be detailed in the following section.

Sensor Power Draw

The power draw of the tool is not a major concern in traditional wireline logging applications, as practically infinite power is available via the wireline apparatus. However, in MWD-type tools, batteries are generally used to provide power, meaning downhole power becomes the number one commodity and is one of the main criteria of sensor selection and design. A sensor with low power consumption is much more likely to be used in a downhole tool, even if its other characteristics are not a perfect fit. In addition, sensors with very low power draw can show performance instabilities, i.e. they can easily become "flakey."

Sensors drawing higher current from the battery are less likely to be influenced by its environment. The same power tradeoff comes into play with sensors that are self-calibrating. Since these additional features eat up more power without delivering additional value (i.e. additional data streams), they are likely to be dismissed.

Size

Sensor size and package (their relative location) significantly influence which sensor type will be used in the downhole tool. A tool can house several different or redundant sensors, as well as their electrical wiring. The maximum diameter of a tool is governed by different hole sizes. All downhole tools are tubular, and hence can either have sensors sitting in pockets or inside sleeves. Many technologies that could be accurately calibrated are simply too large to be used in the downhole environment. Lately, microelectromechanical devices (MEMS) and even nanoelectromechanical devices (NEMS) are becoming available. These developments allow the compression of traditionally large designs to a very small scale.

As promising as these devices are, they are still in their infancies and have shown to be significantly less reliable than their "bigger brothers." Smaller sensor size allows more sensors to be placed in the tools, but they can also be more susceptible to the harsh downhole environment. The required protection around such MEMS or NEMS sensors then offsets some of their size benefits.

Embedding/Mounting

Sensors are attached to the tool's body in multiple ways. For mechanical mounting, sensor bodies can have mounting holes or brackets integrated into the sensor. Some small sensors are available together with a package that can be mounted in a pocket inside the pipe. Some sensors must be hard mounted to the tool, while others are soft mounted (cushioned) and more protected against impacts. The type of mounting is an important consideration in the tool's design phase and influences the sensor outputs.

Software

Downhole data can either be transmitted to surface in real time (using mud pulse, wired drillpipe, etc.) or stored in memory and retrieved only after the bit run. Sensors, calibration, and post-processing systems must be tailored to the type of data display and the software applications. Real-time systems utilize different viewing platforms with specific processing requirements. Data could be visualized on a mobile device through multiple apps, a computer-based setup, or a field-programmable gate array (FPGA)-based system.

Calibration

Calibration is the process of configuring a sensor to ensure that a measured data point lies within a predefined range. Calibration can be accomplished through the use of testing equipment or software (automated). Calibration through software can remove errors from crosstalk of sensors, wiring between sensors and other tool components, or inaccuracies of the sensor itself. Even offset errors can be corrected through system calibration. Calibration needs to be given careful consideration in the design phase of the tool.

In-Tool Computations

Auxiliary systems are systems that provide a support function for the sensor itself, but are vital for the tool; for instance, memory chips that store information that are required for downhole data processing. These auxiliary systems must be able to handle tool calibration and become an important consideration in the design phase.

The selection of the processor (the central processing unit) also heavily depends on the type of calibrations and whether they are carried out within the tool or after the bit run. The more calibrations and other computations are done within the tool (for real-time applications), the more powerful the processor needs to be. Data is corrected on the fly using edge computing methods and streamed out to the receiver. A powerful processor and advanced computations, in turn, consume more power and thus more battery life. If there is no immediate need for corrected data (memory-mode tools), then the raw values of the data are stored, and any operations on the data are done afterwards using specialized software.

Developing Calibrations

The other type of calibration requires manual setups and specific calibration tools. Sensors and tools need to be designed to facilitate the testing process. Off-the-shelf calibration equipment is often unsuitable for testing downhole equipment, so companies need to develop their calibration tools and methods. The calibration equipment ideally simulates downhole conditions. Downhole tools can be up to 10 feet in length. For calibration purposes, the tool often needs to be separated into smaller parts to facilitate testing, so the mechanics of the calibration process become an important variable in designing the tool.

Sources of Errors

Despite careful considerations, some errors in data are still inevitable. The following section introduces the main sources of errors and how these are accounted for in the design phase:

Temperature

Temperature is the number one issue for downhole sensors. While standard downhole temperatures range from around 75 to 125°C, some high-temperature wells heat up to more than 200°C. Sensors show various temperature-based characteristics, which need to be considered before designing the type of embedding for the sensor in the tool. Some sensors may expand or behave differently, depending on the type of mounting. Sensors may have accurate readings under normal conditions but become unreliable in high-temperature environments. The following temperature effects require consideration in the design phase:

1. Temperature-induced physical damage
2. Railing due to temperature
3. Linear temperature drift
4. Nonlinear temperature drift
5. Nonrepeatable drift
6. Sensitivity changes with temperature

Physical Damage

At high temperatures, devices can undergo severe physical deformation or melting if the sensor or some of its elements are not thermally resistant. Once any physical deformation or charring takes place, the sensor is usually irreparably damaged and must be replaced. At the design stage, it can be ensured that the sensor consists of temperature-resistant material. Such a material may still expand, but it isn't permanently affected by temperature changes.

Railing Due to Temperature

"Railing" is a term used when the sensor is incorrectly outputting the maximum or minimum value of its range, which renders it unusable. Many sensors “rail” when they are exposed to temperatures outside their specifications. This usually happens when a sensor is exposed to temperatures exceeding the recommended rating. Data sheets usually list a sensor’s operating ranges as recommended by the manufacturers. The downhole tool provider needs to ensure that these ranges are not exceeded during tool deployment.

Linear Temperature Drift

A commonly observed problem is the temperature-induced drift of measurements. For linear drifts, the offset is proportional to a change in temperature. For example, static gravity measurements can drift from 1 to 5 g as the tool goes into the hole and heats up, and gradually go back to its correct value as the tool is pulled out and cools down. This drift is repeatable every time the temperature changes. The linear nature of this drift can be used for automated calibration. Drift factors can be found in the sensor’s data sheets and are utilized in the design phase. In most cases, these drift factors are verified and refined in a testing process. For linear drifts, linear corrections can be easily implemented and computed. However, such linear corrections are only an approximation and do not correct the data 100 percent.

Nonlinear Temperature Drift

In addition to linear drifts, sensors can show nonlinear drifts. Readings are corrected for nonlinear drifts through approximations by multiorder polynomials. If this type of calibration is carried out downhole, it can be computationally expensive and consume large amounts of valuable power. Again, well known nonlinear drift factors are determined from sensor data sheets and testing procedures.

Nonrepeatable Drift

A nonrepeatable drift is a kind of drift that is not easily predictable. Every time the sensor is exposed to higher temperatures it drifts, but the drift varies. It may be linear or nonlinear following different functions every time. This drift can be related to design errors and makes the sensor unsuitable for use under high temperatures. If temperature-resistant sensors are not available, these errors can still be overcome through complicated calibration techniques. For instance, measurements from other sensors can be used for on-the-fly corrections.

Sensitivity Changes

Temperature also causes a change of sensitivity in a sensor, leading to a change in scaling with temperature. An increment of, for instance, 1 psi then looks like 1.3 psi or 0.7 psi in the sensor’s output. This is an important error to detect and correct. It can significantly change the measurements and is not easily detected as sensor error.

Pressure

Just like high temperatures, pressures of sometimes more than 20,000 psi are a huge source of error for downhole sensors. Sensors have recommended operating ranges for pressures but there are multiple methods for compensation should these ranges be exceeded. Sensors can be pressure sealed, or mechanical or computational compensation methods can be applied.

Sensors can be shielded off mechanically by embedding them into a pressure-resistant case. However, this method adds complexity to the manufacturing process, and space restrictions make it hard to accommodate such cases.

Mechanical pressure compensation is a more commonly used method to correct for errors caused by high pressures. It involves intricate machining and carefully balancing different materials, which adds to the cost of manufacturing. Pressure effects can also be compensated by computational methods, analogous to temperature corrections. Errors caused by pressures tend to look similar to temperature errors, they can be linearly proportional to pressure increases and also follow nonlinear functions.

Shocks

Downhole forces due to vibrations or rough tool handling expose sensors to high-impact loads or shocks. Newer, smaller-sized sensor technology usually has delicate insides, with shock and vibration not only causing spikes and noise in a measurement but physical damage to the sensor, as well. Manufacturers issue shock certification for sensors, which specify the accumulated number of shocks the sensor can withstand. Different downhole conditions and the ability to properly count these shocks make these shock numbers unreliable for practical applications. High-shock environments greatly affect sensor calibration. Soft mounting can cushion some of the shocks, but sometimes sensors need to be hard mounted. The high-vibration environment also forces a complete tie-down of all the wires and harnesses, as they would get damaged during runs if moving freely.

Operational Tool Life

Downhole vibrations pose a challenge not only to drilling itself, but also to downhole tool life. Three differentiated modes of vibration (lateral, axial, and torsional) must be detected and mitigated during the drilling process. Tools can be harmed through fatigue, accumulated cyclic stress loading, and medium-level shocks. Manufacturers have made significant design improvements and are now recording shock data to better predict the half-life of tools and avoid costly failures before the bit reaches the desired depth. Tools can also be damaged by high-impact loads. Backward whirl, a special form of lateral vibration, can destroy tools almost instantly if it is undetected for only a short period of time. Unfortunately, backward whirl cannot be directly measured at surface with commonly used surface sensors and data rates. Certain sensors are critical to the drilling process—if they fail, they need to be replaced without completing the bit run. For instance, failure of wellbore positioning (survey) sensors in an MWD tool usually causes significant NPT. Improving the reliability and accuracy of such sensors is thus a primary driver for drilling performance.

Operations Affected by Design

Tool design is a complex process. In the ideal case, the planning process should start at the end user's data requirements. These requirements then determine data quality specifications[5] (on accuracy, precision, timeliness, etc.). The tool's sensors and calibration techniques then should be designed around meeting these requirements. In reality, however, the tool design determines the manner and methods of sensor calibration, which in turn determines the accuracy of the sensors. This means that the quality of data becomes a mere product of the design process. A lack of foresight or "cutting corners" in the design process will lead to major problems like higher costs, manual data corrections, bad data quality, etc. at a later stage.

Data Processing

Data Rates

Sensors measure an analog (continuous) physical phenomenon at a certain sample rate and an analog-to-digital converter (ADC) turns this continuous into a discrete (digital) signal. The sampling rate of a sensor depends on multiple factors: the sensor design and its built-in processing (filtering) capacities, the ADC, the recording scheme, and the data-transfer or storage process. In some cases, sensors already have a digital output, i.e. they have an ADC built into them. The output data rate of such digital sensors is fixed. An attempt to output higher data rates only provides more data points along an interpolated curve between actual data recordings. The more common sensor type outputs an analog signal and a separate ADC converts it into a digital signal. In this setup, the data-sampling rate depends on the capabilities of the ADC. "Fast" ADCs with high sample rates consume more power than slower ones. The system clock of an ADC ensures that the digital samples are taken uniformly (at the same time intervals). Currently, there is no standardized process available to calibrate these clocks.

Digital Resolution

Digital resolution is the smallest difference between two distinguishable numbers. It is a property of the sensor's sensibility, thus the hardware. If the digital resolution is not high enough, measurements appear to be constant for certain time intervals, as shown in **Fig. 1**. More sensitive sensors are able to deliver high resolution, but it comes at the price of larger data volumes per measurement. Normally, sensor measurements have a 12- or 16-bit resolution, but higher resolutions can be made available if needed. Usually, there is a tradeoff between sample rates and resolution per sample to stay below certain data volumes. These choices depend on the specific data requirements and should be carefully considered for different applications.

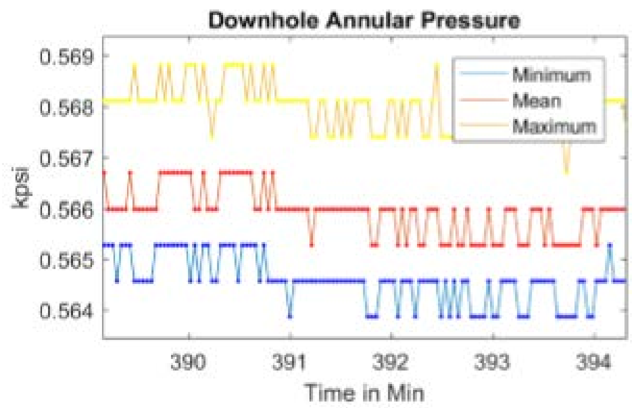

Fig. 1. Example of a signal output whose digital resolution is too low.

Filtering

Filtering is a standard procedure in digital signal processing. It is important if the measurement not only contains the expected variations, but also captures unwanted signals. Filtering then removes data points that vary at certain frequencies and keeps others. There are two different filtering options: hardware filters and software filters.

Hardware filtering requires additional electrical components to be placed in the path of the sensor and the master devices, which control and coordinate all the sensors. Most sensors have built-in hardware filters. These filters often remove high-frequency noise, but their setup depends on the specific application.

Software filtering is a standard process and can be implemented right at the downhole sensor or in a post-processing step. In both cases, the filter needs to be applied to raw data and not any derived or truncated data.

There are different types of filters that can be applied to the data, and their specific frequency cutoffs can be freely adjusted:

1. Low-pass filters remove higher frequencies.
2. High-pass filters remove lower frequencies.
3. Band-pass filters allow data of a certain frequency range to be retained but not anything outside those ranges.
4. Band-stop filters remove data of a defined frequency range, keeping all other frequencies.
5. Notch filters allow removal of a specific frequency, keeping all other frequencies.

Filters are an essential tool to clean unwanted noise or errors from a signal and focus on the important measurements. However, the filtering process can greatly modify the data and is irreversible. The exact same measurement with two different filters applied could be completely different, so filters need to be chosen wisely. Information on the filtering process should be available to the end user of the data.

Error Correction

As described above, nonlinear sensor drift is currently inevitable in some cases, and additional corrections are applied in a post-processing step. These correction methods vary among the different service providers and are currently not standardized or disclosed. A critical correction process is done on data from strain gauges, primarily WOB and torque on bit (TOB). During a connection, the bit is off bottom and the torque or weight on the downhole tool should be minimal. At the rig, the crew identifies that particular moment in a process called “taring.” The driller pushes a button, and WOB and TOB values are calibrated (set to zero). Of course, this method is susceptible to human error, such as selecting the wrong moment or not conducting the taring procedure for certain connections. Another approach for historical data is to correct such values manually or semi-automatically by identifying these points from patterns in the data.

Timestamps

Downhole data only senses a limited amount of parameters. For any analysis, downhole data needs to be time aligned with surface data. For real-time application, the data is recorded in the downhole tool, transmitted to surface, and displayed. Depending on the type of data transmission, the system shows significant linear and nonlinear latencies that are not fully taken into account. When real-time data is stored as historic data for later analysis, the recorded timestamp usually shows the time of arrival at surface, not the time of the measurement.

Tools in memory mode (storing data for post-run retrieval) have clocks that are synchronized with surface clocks before the tool is run. These clocks measure the time that has passed. However, downhole temperature and pressure conditions may also affect the tool’s time stamps. One second can become longer or shorter and sampling may be nonuniform. Post-processing data usually involves manual alignment of downhole and surface data. Indicators such as pressure spikes in both data sets can be used for this process. Such alignment methods do not account for latencies.

Data Limitations

ADC converters turn an analog signal into a discrete signal. Since the downhole weight and torque are measured at a tool above the bit, the correct name should be weight or torque on tool samples. That digital signal is later used to reconstruct a continuous function that should mimic the analog measurement. If the sampling rate is too low, the reconstruction will exhibit imperfection. The Nyquist criterion states that for a perfect transfer of an analog to a digital signal and vice versa, the sampling rate should be at least twice as high as the frequency of interest in the recorded signal. In a system with bandwidth and memory limitations, the number of channels (signal outputs), sample rate, digital resolution, and measurement duration (for memory only) can be adjusted to optimize the information obtained from downhole sensors[6].

Conclusions

Downhole sensors for measuring drilling dynamics are promising to positively impact drilling performance and enable drilling automation. Downhole data is currently underused. Many drilling engineers faced difficulties making decisions based on real-time downhole data or analyzing such data after drilling. Better data quality will result in higher utilization of such data. However, sensors and the process of data collection, processing, and transmission needs can be improved to deliver more useful and reliable data to the end users.

Wellbore positioning and well-logging efforts have shown successes of standardization and transparency of calibration, corrections, and data formats that lead to more reliable data for decision making. Similarly for downhole dynamics data, transparent and standardized calibration procedures could hold the key for improved data quality. Calibration periods should be subject to contracts between operators and service companies, and the need for additional calibration methods, especially during operations, should be identified and new techniques developed.

Some measurements are not yet comparable across different tools and service providers. Disclosing techniques for calibration, sampling, filtering, error correction, and other processing steps is required to use such data as inputs for drilling automation and large-scale data analysis. Metadata (data that describes the data streams) can be embedded in the actual data sets and are a useful tool to communicate sensor design, processing steps, and operational factors to the end users.

Most importantly, operators and other users of data need to define and enforce data quality according to their needs. The design of downhole sensors needs to be based on the requirements of the end users. The higher costs of better sensors that deliver more accurate data can then be justified by operational savings. Such efforts require interdisciplinary initiatives and collaborations across different types of companies. Tool manufacturers need to better involve sensor suppliers so that such sensors can be tailored to applications in harsh downhole environments. This supply chain improvement process has been successfully implemented for many other services and products and in many other industries. We are confident that the drilling industry will follow these footsteps as soon as it fully realizes the true value of downhole data.

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