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Detection and Prevention of Drilling Problems through Real-time Modeling

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Abstract

Stuck pipe, hole collapse, lost circulation, and kicks continue to cause drilling problems, and are the source of considerable lost time during well construction activities. These problems often seem to occur with little or no warning. However, early symptoms often do exist, but are not easily seen in the raw sensor data available to the driller (*i.e.* Hookload, Surface Torque, Standpipe Pressure, Pressure-While-Drilling, Pit Levels). If symptoms can be detected early enough, actions can be taken to proactively prevent the problems from occurring.

This paper investigates the use of calibrated real-time torque and drag, hydraulic, and thermodynamic modeling together with advanced real-time engineering calculations to assist drilling teams to detect symptoms of drilling problems at an early stage. The early detection of symptoms can then be used either to provide warnings to the drilling team, or as an input to an adaptive drilling automation system that responds to changing hole conditions.

Introduction

Stuck pipe, hole collapse, lost circulation, and kicks continue to cause drilling problems, and are the source of considerable lost time during well construction activities. These problems often seem to occur with little or no warning. However, early symptoms often do exist, but are not easily seen in the raw sensor data (*i.e.* Hookload, Surface Torque, Standpipe Pressure, Pressure-While-Drilling, Pit Levels). If symptoms can be detected early enough, actions can be taken to prevent the problems from occurring.

The symptom detection method presented here is based upon the use of a single integrated and *calibrated* torque and drag, hydraulic, and thermodynamic model while drilling.

Real-Time Modeling

Real-time Modeling provides the drilling support team with a reference of what each of the rig sensors should be reading based both on current conditions and on the driller's actions (pipe movement, pump activity, pipe rotation). These "virtual sensor" outputs can be used by the drilling team as a baseline with which to compare to the actual sensor data.

Real-time Modeling also provides "virtual sensor" readings in locations where no sensors are currently deployed. For instance, the modeling can continuously calculate the dynamic pressure behavior at all depths in the well based both on the current conditions (i.e. mud properties, trajectory, actual well geometry, tubulars in the well, temperature profile and thermodynamic effects), and on the drillers actions. The pressure behavior is critical information in order to keep the pressure in the well within a safe geo-pressure window at all depths within the exposed openhole section. For simplicity, the pressure is presented as equivalent circulation density (ECD) and equivalent static density (ESD).

Real-time modeling's foundation is based upon drilling engineering principles that have been in use for decades, but that have been uniquely refined and now applied in real-time while drilling. Until recently, the technology did not exist to perform the required integrated modeling *in real-time*. This torque and drag, hydraulic, and thermodynamic modeling has been typically performed only during predrill planning, because the required computing power and algorithms did not exist to continuously solve the finite difference equations in real-time. Another issue is that many of the modeling parameters are *unknown* without performing an in-situ calibration.

The capability now exists to perform this calibrated modeling in real-time during all well construction activities (*e.g.* drilling, tripping, circulating, sliding, coring, displacing mud). This is possible with real-time data streams from the rig connect to the model

Deviations between the output values modeled in real-time and the measured values provide engineers with the earliest possible evidence of deteriorating hole conditions. This evidence also provides the foundation for drilling automation for the prevention of drilling problems

Model Building

The first step in performing real-time modeling is to build the integrated model. Model inputs include the following information:

- Bottom Hole Assembly, BHA information
  - Length, ID, OD and weight of the elements in BHA, DC
  - Bit nozzle size
- Length, ID, OD, weight of the drill pipe and HWDP
- Geo-pressure Window
  - Fracture gradient
  - Formation tests (FIT, LOT, XLOT) if available
  - Pore pressure gradient
  - Collapse pressure gradient
  - MDT or RFT Tests if available
- Geothermal profile
- Wellbore trajectory
  - Measured Depth, Azimuth & Inclination
- Casing architecture
  - Casing data, suspension depths and lengths
  - Riser Length, ID, OD
- Open hole size and length
- Drilling fluid properties
  - Oil or water based
  - Type of base oil and related PVT table
  - Full Mud report including rheology, yield point, density and temperature, Oil/water ratio, solids, salts type and concentration, Gel strength
- Rig data
  - Block weight,
  - Drill floor elevation
  - Water depth in case of offshore rig.
  - Air gap
- Daily drilling reports

As Real-time Modeling is a transient calculation, real-time data streams capturing the actions taken on the rig must be used to drive the model. These data feeds include, but are not limited to, block height, RPM, and input flow rate. With these data inputs, the model can be used to provide a continuous calculation of the outputs mentioned above (*i.e.* virtual hook load, virtual pit level, virtual surface torque, virtual standpipe pressure, *etc*) that can be compared to the real-time data and provide calculations of the data where no sensors are deployed (*e.g.* mud density, cuttings location, ECD, ESD) at all depths in the well.

Model Calibration

If all model parameters are correctly known, the modeled data should match the real-time sensor data. Unfortunately, many of the pre-drill model parameters are not known accurately enough to model in real-time for symptom detection. The actual weights, IDs, ODs, of the down hole tubulars are based on engineering tables, but do not reflect the equipment actually deployed in the well. Sliding and rotational frictions and hydraulic frictions can be estimated but are not well known.

Fortunately these unknown parameters can be determined by performing a real-time calibration. The first step is determining specific situations during the well construction process that are ideal for calibrating specific parameters. For instance, rotating the string off bottom eliminates sliding frictions and the true linear weight of the drill string and BHA components can be determined. This weight calibration, along with the calibration of a number of other model parameters, such as lifting forces on the string caused by circulation and the pressure losses inside the drillpipe and in annulus, are performed automatically and in real-time.

Figure 1 captures the process of calibration, monitoring, and symptom detection based on real-time modeling. Note that as the parameters are calibrated, the modeled data and the sensor data almost overlay. Real-time modeling can provide a reference baseline for surface torque, hookload, pit levels, PWD, and/or Standpipe pressure. Deviations between modeled and actual for any of these sensors can be an indicator of deteriorating conditions.

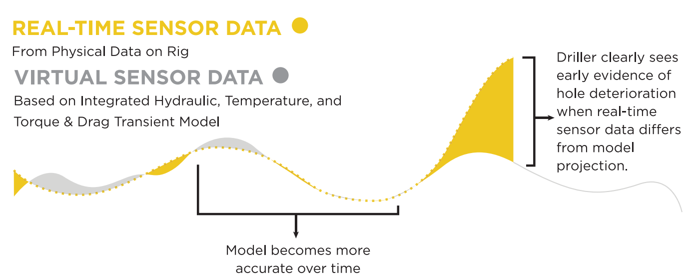

Figure 1: Deviations between Real-Time Sensor data compared to modeled data is a very good indicator of deteriorating hole conditions that may lead to later drilling problems.

Pre-drill torque and drag, and hydraulic modeling tools are not suitable for use in real-time without continuous in-situ calibration of essential model parameters. The examples shown in this paper are based upon a system that automatically calibrates the model parameters based on current conditions.

Additional Engineering-While-Drilling Calculations

We have seen that comparison between modeled data and actual data provide insight to the current conditions in the well that may be deteriorating. For instance, an actual standpipe pressure that is higher than the calibrated “virtual standpipe pressure” may be an indication of poor hole cleaning that could eventually lead to a packoff. The same situation could also be identified by a sensor hookload measurement that is lower than the modeled hookload measurement. This can be due to obstructions in the annulus, causing a small increase in downhole pressure, giving additional lifting forces on the string (piston effect within the well).

Additional calculations can be performed based on this comparison of modeled data to actual sensor data. The deviations can be used to automatically calculate continuous **direct physical indicators** of hole problems. The continuously calculated data can include the following indicators:

- Standpipe Pressure Deviations
- Sliding Friction
- Rotational Friction
- Free Rotating Weight Deviations
- Pit Level Deviations
- Hole Cleaning Index

These six indicators can be provided in real-time to the drilling team. Reduction of the raw data to a few indicators provides the driller with important information without information overload

Prevention of Kicks, Hole Collapse, Lost Circulation

The prevention of kicks, or hole collapse is primarily a focus on keeping the equivalent static density (ESD) above the maximum of the pore pressure gradient or collapse pressure gradient across the entire open hole section. The prevention of lost circulation is primarily a focus on keeping the equivalent circulating density (ECD) below the fracture gradient across the same open hole section.

In most drilling operations, the only downhole pressure measurement that may be recorded is at the bit (*i.e.* PWD in the BHA). Pump startups, pipe movement, thermodynamic effects, cutting transport, mud gelling, and other effects can cause the transient pressure in the well to vary significantly across the entire wellbore.. Calibrated transient modeling provides a continuous calculation of the ECD and ESD at all depths. These virtual outputs are then compared to the geopressure window to create additional outputs showing both the minimum gap between the ECD and the fracture gradient (and the depth at which this occurs), and the minimum gap between the ESD and the limit defined by the maximum of the pore pressure and collapse pressure. The drilling team monitor these outputs to continuously see how the actions taken on the rig affect the pressure in the well at all depths and at all times.

The model results can also be used to continuously calculate the maximum drillpipe, casing or liner running speeds, and to calculate the maximum flow rate that will keep the well in a safe condition. These safe guard limits can be used either as dynamic guidelines for the driller, or interfaced directly to the drilling control system (DCS) to protect the well from unsafe actions. If interfaced to the DCS, it provides an automated drilling system that actually responds to changing well conditions.

Prevention of Stuck Pipe

Hole collapse and/or poor hole cleaning are frequent reasons for stuck pipe incidents. The careful monitoring of downhole pressures as described in the previous section, helps to ensure that the pressure does not drop below the collapse pressure.

The modeling can also provide very early indications of poor hole cleaning. The real-time transient modeling calculates the expected hydraulic pressure at the bit considering:

- multi-phase fluid composition
- fluid velocities
- mud compressibility
- thermal expansion/contraction
- mud density variations due to cuttings proportion
- pipe movement
- Other effects such as gelling.

If the measured pressure at the bit begins to deviate from the modeled pressure, it can be a good indicator that the hole is not being cleaned properly. Deviations in hookload and standpipe pressure also provide additional supporting evidence. Direct indicators are also calculated and poor hole cleaning will often show up as a change in hole cleaning index, increased sliding friction, and a deviation in Free Rotating Weight.

Fingerprinting (or overlaying) is a common method for detecting deteriorating hole conditions by comparing sensor readings from one connection to the next. This is a good technique for detecting quick deterioration, but often fails to detect a gradually deteriorating condition from poor hole cleaning. In the case of gradual deterioration, a comparison of the pick up weights at each connection to a continuously calculated roadmap is needed..

The plot below shows the hookload pickup weight at each connection plotted vs depth for a North Sea well. In this example, the hookload decreases gradually as the drillstring is pulled out of the hole. Standard real-time monitoring would suggest that there are no problems on the horizon.

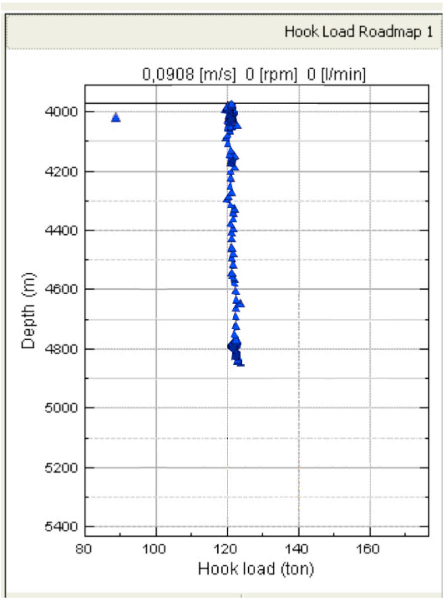

Figure 2: Plot of hookload vs depth at each connection. The raw data alone does not provide any indication of upcoming hole problems.

If we now plot the expected hookload based on modeling on the same plot, we can see that as we pull out of the hole the actual hookload begins to deviate from what is expected from the model. This is a slow gradual deterioration as cuttings or cavings are being dragged up by the BHA.

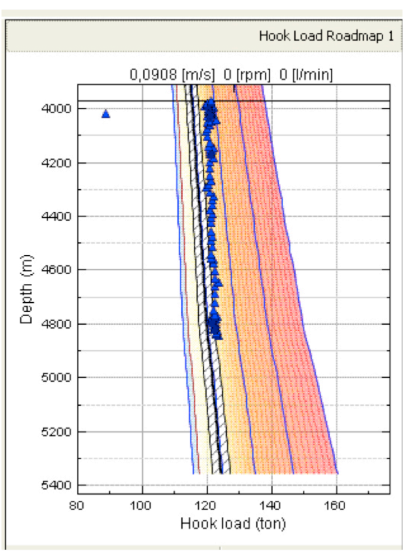

Figure 3: Same data as in Figure 2, but with modeled with a modeled hookload underlay (Heavy Line). Note the deviation between the modeled and actual hookloads. This is an indicator of poor hole cleaning of cuttings and/or cavings.

We can also use the difference between the modeled and actual data and calculate the sliding friction factor. This friction factor is plotted below as a direct indicator that the hole condition is deteriorating and there is an increasing risk of stuck pipe.

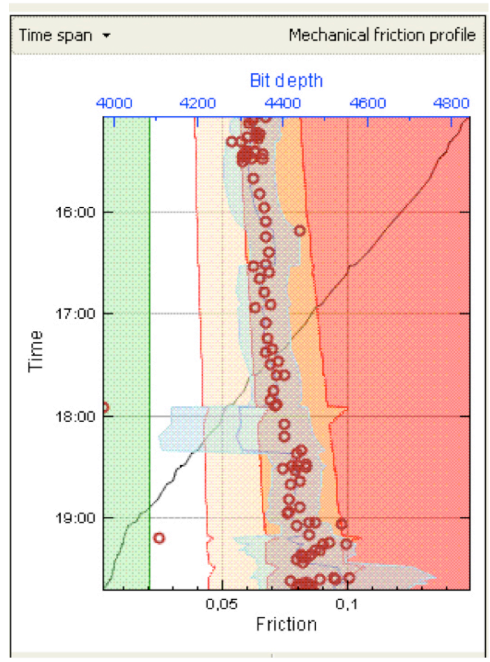

Figure 4: Using the deviations between modeled and actual hookloads (Seen in figure 3), further calculations can provide the sliding friction index with time. In this case,we can see this friction increasing from .06 to .08 over a period of four hours. This is plenty of time to take action prior to running into a packoff situation.

Indications of deteriorating conditions such in this example these are often seen days or hours prior to any overpulls or torque spikes seen in the raw data. Actions can be taken (*e.g.* change in RPM, flowrates, etc.) to help the hole cleaning. Feedback from the actions can then be seen as an improvement in the direct indicators (such as decreasing sliding friction) confirming that the action taken was successful.

Detection of Events

The primary objective in performing real-time modeling and engineering calculations is the PREVENTION of drilling problems rather than in the detection of the event when it occurs. Unfortunately, symptoms are often missed or the event occurs so quickly that there is no time to prevent it. Real-Time modeling also helps in these situations by providing DETECTION of these problem events earlier than other monitoring techniques.

For example, variation of pit volume is a prime indicator of lost circulation, kicks, or influx events. However the detection of gains and losses at the pit level can be difficult because of the transient behavior of hydraulic system. These effects include the compressibility of the drilling mud, volume changes due to thermal expansion/contraction, cuttings removal, and/or the retention capacity of the return flow-line, shakers, sand-trap, degasser, and transfer pit. All of these effects are transient and can cause substantial variations of the active pit volume that may be interpreted as gain or loss while they actually have natural origins.

By taking into account all of the physical effects described above, the use of deviations between the actual and modeled pit level is a better indicator of problems than pit level monitoring alone.

With real-time modeling, pit level monitoring is improved in two ways:

- Elimination of False Warnings: Warnings generated due to changing pit levels due to natural origins are not associated with losses or kicks . Comparison to modeled reference "Virtual pit level" eliminates these false warnings.
- Detection of events within the "normal" pit level variation that would be missed with standard pit level monitoring. If pit level is staying constant, but the modeling is showing the pit level should be decreasing due to cuttings removal or other natural reasons, it is an early indication of a kick that would not be detected using pit level thresholding alone.

Another possible early indicator of a kick could come from a comparison of the modeled ECD at the bit and the measured downhole ECD. The influx of gas or fluid into the annulus would alter the multiphase fluid composition in annulus, causing a change in density and rheology. This change would be reflected in the comparison plot between modeled ECD and measured ECD at the bit. This effect provides real-time evidence soon after the influx enters the wellbore rather than some time later when the effects are seen at the pit level.

Real-Time Modeling in practice

In practice, the use of real-time modeling can be part of an exception-based monitoring program, which is a generally accepted engineering technique to identify conditions that may lead to future problems. This technique consists of comparing measured values from sensors to expected values in search of deviations.

After building the model using the current data describing the rig and current environment, the model is driven using a real-time data stream. Typically this is performed as a remote support operation using a WITSML, WITS0, or OPC data stream. No equipment or personnel is required at the rig site.

The WITSML data stream conveys not only the data to drive the model but also contains all available surface and downhole measurements streamed in real-time.

This advanced monitoring is a complex engineering-while-drilling support function where the entire drilling process is modeled in real-time. The modeling includes complex mechanical, hydraulic, and thermodynamic effects including HPHT effects in the mud, driller's actions, hydraulic and mechanical frictions, all in one integrated model.

The communication back to the driller or drilling team includes warnings of potential deterioration of the well conditions along with calculated indicators such as plots of sliding friction, hole cleaning index, pit level deviations, etc.

Drilling Automation

We have seen that real-time modeling can provide dynamic guidelines on expected hookload, surface torque, ECD, and other parameters. We have also seen that it can provide guidelines related to maximum running speeds for POOH (Pull out of hole) and RIH (Run in Hole) operations and maximum flow rates.

The next logical step is to automatically inform the Drilling Control System of this information to allow automatic reaction to changing conditions to keep the well bore safe.

This automated drilling system can perform the automated functions such as:

- Keeping the ECD and ESD within the geopressure window by controlling/restricting the hoisting speeds and pump startups
- Reacting quickly to dynamically changing thresholds for hookload and surface torque

For example, the driller may attempt to ramp up the pump flow rate too quickly, risking fracturing the formation and causing lost circulation. The system knows the geopressure profile, and can calculate the ECD based on the driller's action. The system takes control and ramps up the pressure in a safe and controlled manner.

Conclusions

Problem events such as stuck pipe, lost circulation, fluid influx, or hole collapse are often preceded by symptoms that are extremely hard to detect using raw data alone. There are too many factors affecting the measurement that need to be taken into account. Modeling these effects in real-time allows the drilling team to focus on deviations from the model knowing that these other factors have been accounted for. By detecting symptoms earlier in their development, actions can be taken by the driller to avoid problems.

Problem events also may occur suddenly as a result of an action taken by the driller (too high pipe velocity, pump startups, etc.). A full understanding of the expected consequence of these actions is possible by performing calibrated modeling in real-time, and can help prevent problem events from occurring by dynamically setting parameters in the Drilling Control System to automatically react to changing hole conditions.

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Nomenclature

BHA = *Bottomhole assembly*
ECD =*Equivalent Circulating Density*
ESD =*Equivalent Static Density*
EWD = *Engineering While Drilling*
FIT =*Formation Integrity Test*
LOT =*Leakoff Test*
OPC = *OLE for Process Control*
PWD = *Pressure While Drilling*
SPP = *Standpipe Pressure*
WITS0 = *WellSite Information Transfer Standard (Level 0)*
WITSML = *WellSite Information Transfer Standard Markkup Language*

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