Automatic Real-Time Drilling Supervision, Simulation, 3D Visualization and Diagnosis on Ekofisk

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Abstract
eDrilling is a new and innovative system for real time drilling simulation, 3D visualization and control from a remote drilling expert centre. The concept uses all available real time drilling data (surface and downhole) in combination with real time modeling to monitor and optimize the drilling process. This information is used to visualize the wellbore in 3D in real time.

eDrilling has been implemented in an Onshore Drilling Center in Norway. The system is composed of the following elements, some of which are unique and ground-breaking:

- An advanced and fast Integrated Drilling Simulator which is capable to model the different drilling sub-processes dynamically, and also the interaction between these sub-processes in real time.
- Automatic quality check and corrections of drilling data; making them suitable for processing by computer models
- Real time supervision methodology for the drilling process using time based drilling data as well as drilling models / the integrated drilling simulator
- Methodology for diagnosis of the drilling state and conditions. This is obtained from comparing model predictions with measured data.
- Advisory technology for more optimal drilling.
- A Virtual Wellbore, with advanced visualization of the downhole process.
- Data flow and computer infrastructure

eDrilling has been implemented in an Onshore Drilling Center on Ekofisk in Norway. The system has been used on several drilling operations. Experiences from its use will be summarized and presented. This paper has main focus on utilization of an advanced flow model for real time supervision and control of ECD and ECD related effects.

Introduction

The southwestern part of the Norwegian continental shelf, called the Ekofisk Area, contains eleven major chalk fields. The Ekofisk field is the first and main discovery, discovered in 1969 and put on production in 1972. The fractured chalk reservoir lies at a depth of 9500 – 10700 feet and is approximately 11.2 x 5.4 kilometers in area, with production coming from two zones Ekofisk and Tor. It is one of the North Sea Giants with a STOIIP of 7 MMBO!

Currently there are 4 fields in production, 4 fields abandoned with current production around 325,000 bbls per day of oil and 350 scf of gas per day. Water injection is currently used to maintain reservoir pressure, and approximately 900,000 bbls of water are injected each day.

There are over 150 wells that have been drilled on the Ekofisk, and due to the complexity of the field, with its numerous faults and fracture networks, location of injected water, and pressure uncertainties, all result in well placement challenges.

New wells are being drilled both as injectors and for production from newer facilities, and from jack-ups. Much of this drilling is supported from the Onshore Drilling Centre (ODC) located onshore about 280 Km from the field. It is connected to
offshore by high bandwidth fibre optic cables which allow high levels of communication and real time data/information transfer.

It was in 1998/1999, a 1143 kilometer long fibre optics cable with 24 fibre strands was run from Kaarstoe on the west coast of Norway, via the North Sea oil platforms Draupner, Ula, Ekofisk, Valhall and Murdoch, to Lowestoft in the UK. COPNo1 utilizes part of the capacity of one pair of strands in this cable for a 2 x 155 Mbits/sec data connection between the Ekofisk field and the offices onshore. The Ekofisk area, which consists of many platforms, is interlinked with fibre optic connections or high-speed radio links, in turn meaning that the lowest bandwidth available to shore from any ConocoPhillips Norge platform on the Norwegian Continental Shelf is 155 Mbits/sec.

This huge increase in available bandwidth, compared with traditional offshore installations, has revolutionized the communication between onshore and offshore.

Key types of services delivered through the cable include:

- Telephony
- Video conferencing
- Closed Circuit Television (CCTV)
- Direct communication between handheld UHF radios offshore and phones onshore
- Wireless video and audio communication between VisiWear units offshore and PCs/video conferencing equipment onshore
- Wide variety of real time data transfers
- Remote support / remote control

Video conferencing, once regarded as too unreliable or cumbersome to use - or simply not feasible in an offshore environment - is now a business critical service within ConocoPhillips in Norway. About 2,500 video conference meetings are held each month, the majority of these between onshore and offshore. Moreover, the demand for point-to-point and multi-party conferencing continues to increase.

This technology enables multiple disciplines ranging from Operation Geologists to Directional Drillers to carry out much of their work remotely from the centre.

ConocoPhillips Norge has been very supportive towards new technologies which can improve the effectiveness of drilling operations and can reduce drilling problems. eDrilling is the prime example of this.

**Real Time modeling**

The key elements of eDrilling are real time simulation, visualization in a virtual wellbore and decision support. The infrastructure allows for simulation of the drilling sub-processes by integrated drilling models driven by the process itself. This RT enabled Integrated Drilling Simulator creates a “mirror” of the drilling process itself, and gives important information on key drilling parameters like hydraulics profile (ECD), temperature profile, friction conditions along the drillstring and wellbore, cutting transport conditions, well instability tendencies, pore pressure ahead of drill bit, optimal ROP; all in real time.

The system also makes automatic diagnosis of upcoming drilling problems by combining real time simulations with drilling data.

The virtual wellbore is another key element of eDrilling. The 3D visualization of the drilling itself (drillbit, string, BHA etc) in real time is supplemented with VR visualization of simulation results. This makes the virtual wellbore the key tool to communicate well status as well as inform across boundaries (drilling, geology, asset team ...) during the drilling operation.

**Data quality.** Quality of real time data from external sources into the eDrilling system is important because models need good input data to produce accurate and reliable results. Thus one benefit of using models online is that data deficiencies, including signal transmission errors, are revealed and can be addressed or accounted for. When using the eDrilling system data quality is addressed in several ways:

- Improve data sources and signal transmission
- Filter invalid data
- Correct data before used by models

The last two bullet points are addressed by a dedicated data quality module (DQM), which corrects data by various calculations. Important examples are:

- Calculation of bit position based on a combination of detailed real time tally information and automatic status detection. The nominal depth is checked vs. changes in hook position when not in slips. This will reduce the need
for manual bit depth corrections to a minimum, which is important to avoid transient responses from dynamic models. A review of historical drilling data has revealed a need for better bit depth calculation, especially when tripping.

- Correction of string length due to stretching and thermal effects. With accurate calculations the real position will be known in addition to the nominal position, and the two may depart significantly. This does not matter much as long as running with one string, but when changing to e.g. a completion string or wire line, corrections will improve the correspondence of depths with different strings.

Successful testing of the DQM has been done on data from the actual drilling operations. Figure 1 shows an example of calculation of the effects of stretching and thermal expansion.

eDrilling System infrastructure
The Data Distribution System (DDS) is the kernel for data distribution in the eDrilling system. Clients can subscribe and publish data to the DDS Server. External data is published into the Server via Interface clients. At the Ekofisk pilot OPC and ODBC clients are used for this purpose. WITS data from Halliburton (Sperry Sun) are fed into the system via the OPC client and Peloton WellView data are fed into the system via the ODBC client. In the near future the DDS system will have a WITSML DDS client enabling WITSML communication. Below is a typical eDrilling System infrastructure.

3D Visualization of Ekofisk Complex with 2/4-X
The eDrilling 3D engine has the capability to import 3D models with high complexity and zoom (fly into) subsurface details. See below for some typical examples:
Well description with drilling experiences
The well used for this presentation is a sidetrack from the main well bore. The operational sequence covered in this presentation is to drill out the shoe track and continue to drill into the reservoir. The presentation covers three days of operations from 12:00 2nd September to 12:00 5th September 2007. The drillstring consisted of an 8 ½” x 9 ½” Geo-Pilot steering assembly, together with a formation pressure tester and MWD pulse telemetry system.

Oil based mud was used. The mud in the well at the start of this sequence had a density of 14.7 ppg. This was displaced with mud having density of 9.5 ppg at the start of this sequence. Mud density fell slightly during this sequence and was later increased first to 10.0 ppg and later 10.2 ppg.

Inclination angles for this section were stable around 9 degrees with a slight swing in azimuth to the right.

Many problems were encountered with this well, both before, during and after this section. Problems include mud loss, gas influx, tight hole, and equipment failure.

Supervision of ECD
An advanced pressure and temperature model, optionally with automatic or semi-automatic calibration, will run continuously during drilling operations, and help converting raw data to useful information easier and more reliably. A comprehensive presentation of the model is given in Ref. 4, and several applications are presented by Refs. 5-10, but then not integrated in the eDrilling system. The example discussed here is from a real well with the model integrated in the eDrilling system.

Pressure measurements along the flow trajectory, i.e. standpipe pressure and PWD pressure (if available) are used for the calibration of the flow model, which calculates pressure at all positions along the flow trajectory. Pressure in the open hole will be presented as a color layer on the 3D drawing of the well and, optionally, as 2D depth plots. In both cases defined such that it easily relates back to the most updated data on pore or collapse pressure on the lower side, and fracture pressure on the upper side. The color code will give a clear indication as soon as well pressure is getting too close to lower and upper boundary somewhere in the open hole.

Similarly the temperature model will be calibrated, primarily to ensure more accurate calculation of pressures and volumes, but as a secondary effect it will give valuable information related to the environment of downhole instrumentation and wellbore stability.

Figures 2-4 show flow model results when replaying data from the well on Ekofisk through the eDrilling system. A drilling and reaming sequence of 1.5 days is shown. The decreases and increases in pressure after 3.1 days are due to mud density increases. In this sequence the model reproduced variations accurately without continuous tuning, only a constant 10 % correction was applied. There is some deviation between model and data shortly after 2.75 days, most likely due to inaccurate information on mud density changes. The good match with measured standpipe pressure supports the calculated bottomhole EMW. The model calculates also ECD at other positions along the open hole, and the result is compared to the most recent collapse, pore, and fracture pressure available. The 3D view will then clearly warn operators and engineers when getting close to or outside borders, see Figure 8.

Pressure points measured while drilling are added in Figure 4. Gas return was observed in this period, and mud density was increased several times, which seems consistent with the fact that some pressure points are above calculated EMW. See further discussion in the section on diagnosis below. With an accurate prognosed pore pressure profile the system would give early warnings on these events.
Diagnosis of problems
The availability of real time enabled advanced models and methods prepare the way for much a more robust and reliable diagnostic system. Early versions of the following sub-systems have been implemented as integrated parts of the eDrilling system:

- **Improved volume monitoring.** The system monitors the difference between measured and calculated active volume. Calculations account for changes in temperature and running string volume in the well, such that changes the monitored difference will be due to other effects like kick or loss. Volume changes due to filling and emptying of surface lines is still a significant effect not accounted for by the model, but this is being worked on through a combination of advanced modeling and artificial intelligence methods, see the example below. The combination with an advanced calibrated pressure and temperature model will reduce the number of false alarms due to thermal effects, and it will unmask a loss or gain that is masked by thermal effects.

- **Improved hole cleaning monitor.** The system monitors trends in hook load and torque taken while drilling and at three distinct times of connections: Lift up, rotating off bottom, and slack off. An advanced torque and drag model will calculate expected values, and help to reduce uncertainty due to differences between the exact timing of different connections.

- **Improved detection of impending stuck pipe and early detection when going stuck.** Again use of advanced calibrated flow and torque/drag models will help clarify the real signals, and give early warnings.

- **Improved ROP monitoring.** The system will detect non-optimal ROP due to for example vibrations caused by too high WOB, see separate section above.

The benefits of this system are several:

- Earlier warnings
- More reliable warnings, i.e. fewer false alarms and fewer real events with no alarm
- Continuous focus on the process also through tedious periods that are considered low risk by the drilling crew.

Figures 5-6, which zoom in on the last part of the sequence shown above, show an example on how active volume changes significantly when pump stops and pump rate changes. The eDrilling system will address this through modeling, artificial intelligence, and visualization of signatures to provide an easier and more reliable way to distinguish for example a gain during a pump stop from a normal pump stop increase of volume.

An interesting observation is that the increase in active volume when reducing pump rate was significantly higher in the period when mud density was increased several times due to gas return, than shortly after drilling out of the casing shoe a couple of days earlier, see Figure 7. A certain volume increase due to emptying of surface lines is expected when reducing pump rate or stopping pumps, but this effect is more or less independent on what happens in the well. The extra “gain” seen may be due to expansion of gas already in the wellbore, or due to drilling fluid flowing in and out of small fractures. The latter effect is known as wellbore breathing. These effects will be analyzed further, and a reliable interpretation method based on a combination of an advanced flow model, artificial intelligence, and adapted fingerprinting is under development. One major challenge is to develop a method that depends as little as possible on pump rates and rate of change of pump rates.

Supervision of T/D
The SINTEF Torque and Drag model is based on the standard soft-string model (Ref. 11) with several extensions. The following extensions are implemented in the model:

- Helical buckling model with post-buckling capabilities accounting for the 3-dimensionality of the wellbore path (Ref 12)
- Torque-buckling interaction (Ref 13)
- Wall climbing effects
- Friction factor back-calculation
- Calculation of normal string-wellbore contact forces along the string
- Tri-axial von Mises stress calculations along the string, including the effects of hydraulic pressures and buckling
- String length correction due to axial loads, buckling contraction, thermal expansion and hydraulic pressures

The model is applied for the calculation types:

- Calculate WOB with input of hook load or vice versa.
- Calculate bit torque with input of surface torque or vice versa.
• Back-calculation of friction factor with input of measured surface and bottom hole weights or torques. Friction factor can be monitored with warnings issued on unexpected changes.
• Bit depth correction due to string elasticity. More accurate bit depth will increase value of LWD.
• Initial calibration of rig specific parameters, such as model parameters for force/torque transfer from top drive system to string.

Benefits are realized through

• Comparing measured hook load with calculations while tripping, and warn if unexpected deviations occur. Compare with earlier trips to identify expected effects like dog-legs.
• Comparing measured and calculated hook load and torque during connection tests, which typically involves pick up, rotating off bottom, and slack off. Trends in data and calculations are used to obtain early indications on poor hole cleaning.
• Comparing measured torque and ROP while drilling with calculated results to get early indications on poor hole cleaning. Both the torque/drag model and the bit/ROP model will be involved.

During operations results from the T/D model are visualized dynamically in the virtual wellbore (total stress, von Mises stress and normal forces).

ROP Monitoring
While drilling a well, the rate of penetration will vary. Some of this variation is due to variations in the formation parameters and some is due to variation in the drilling parameters. The important formation parameters are the compressive strength and the formation pressure. Drilling parameters include a description of the bit, the weight on bit, the rotary speed, the borehole pressure, the mud flow rate and viscosity. Analysis of these variations, intentional or incidental, can give more information on conditions down hole than is generally assumed possible. Time-based logging data is a prerequisite for this analysis. An example of ROP analysis performed on drilling data from Ekofisk is given in Ref.1.

Conclusions
A comprehensive system with multiple models and a 3D visualization application integrated with live drilling data in real time has been developed and demonstrated on data from a real well. An immediate benefit of the system is easy access to very advanced modeling for drilling crew and experts who monitor operations from onshore or on the rig. This paper uses dynamic flow modeling as an example to illustrate how a slightly calibrated model reproduces accurately standpipe pressure, and thus most likely gives an accurate picture of open hole pressure, which can be automatically compared to expected collapse, pore and fracture pressure along the open hole section.

Furthermore, there is an ongoing development of a more automatic diagnosis system, which combines results from modeling and real time data to give early warnings on and reliable interpretation of unwanted events. This paper discusses and illustrates how safer detection of gains and losses when stopping pumps is possible by using a combination of transient flow modeling, artificial intelligence, and improved footprinting.

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References


11. Xiaojun He and Áge Kyllingstad; SPE 25370; SPE Drilling & Completion, March 1995, pp. 10-15


Appendix. Figures

Figure 1: Bit depth before and after correction due to stretching and temperature effects.

Figure 2: Pump rate, 1½ days of drilling
Figure 3: Standpipe pressure, same period as Figure 2.

Figure 4: Bottom hole equivalent mud weight, same period as Figure 2.
Figure 5: Pump rate.

Figure 6: Active volume, same period as Figure 5.
Figure 7: Pump rate and active volume, on three different pump stops, one early and two late.
Figure 8: A kick alarm as displayed by the 3D view. The message “Drilled Kick Possible” pops up when calculated well pressure is close to or below pore pressure somewhere along the open hole, but no gain has been detected yet.