2nd IFAC Workshop on Automatic Control in Offshore Oil and Gas Production,
May 27-29, 2015, Florianópolis, Brazil

Use of High Fidelity Models for Real Time Status Detection with Field Examples from Automated MPD Operations in the North Sea

Knut Steinar Bjørkevoll*

**Sintef Petroleum Research, Bergen, Norway (Tel: +47 928 96 158; e-mail: KnutSteinar.Bjorkevoll@sintef.no).*

Abstract: The paper discusses use of comprehensive real time mathematical models in automated drilling operations, with example from successfully run operations in the North Sea.

Keywords: Mathematical models, robustness, calibration, automation, decision support systems.

1. INTRODUCTION

Complex real-time mathematical models for drilling have been used in several North Sea operations to help automating parts of operations where availability of downhole measurements in real time is very limited at best. Thus real time calculations may provide the information needed to keep within pressure boundaries in the open hole, and thereby both help optimizing the operation with respect to time, and help reducing the risk of humans making wrong decisions with regards to keeping pressure at an optimal level in the open hole.

The backside of this is cost and risk introduced by the complexity of automatic systems with advanced mathematical models within the control loop. Accordingly work is ongoing to simplify the architecture of automated drilling systems. The complex model is moved outside the control loop and replaced by a simplified and very robust algorithms, which can run the system based on downhole real time measurements. This is fully in the line with the author's view, and will not to be debated here.

The main point to be made here is that complex real-time high-fidelity models may add significant value if implemented in a way that handles the various related challenges adequately.

The concept is then a two-model concept, where the comprehensive model is replaced by a simplified model in the control loop, while the comprehensive high-fidelity model still runs in real time, but is separated from the control loop.

The simplified model will handle quick responses to things like changes in pump rate and string movements, while the full model will run in parallel to provide information on longer term effects. See for example Gjerstad et al (2012) for an earlier work on developing an accurate simplified model. Control loop parameters may be adjusted based on calculations with the comprehensive model, but only with a time delay that is sufficient for a thorough (and partly or fully automatic) quality assessment of calculations with the full model.

Benefits of the concept include that the complex models may

- Help filling in more accurately between sensors in time and space.
- Provide synthetic "sensors" in runs with no downhole sensors, like running casing, liner or completion, and cementing casing or liner.
- Add redundancy to automatic systems.
- Improve understanding of well status.

Realizing these potential benefits is only possible if the implementation is done in a very robust way; the overall objective being to add benefits from calculations with advanced models without reducing stability, robustness or user operator-friendliness of the overall system.

Robustness means among others understanding and detecting a number of anomalous situation, and ability to adjust to changing conditions in the well. A real time high-fidelity mathematical model can help obtaining this, again under the condition that challenges and pitfalls are handled adequately.

The comprehensive type flow model has been used in several contexts in the North Sea, including automated Managed Pressure Drilling (MPD) by Statoil through reservoirs where heavily depleted segments were expected, see Syltøy et al (2008) and Bjørkevoll et al (2008, 2010), and for decision support and automation on Ekofisk and Statfjord, see e.g. Rommetveit et al (2009).

The same comprehensive model has been embedded in a high-fidelity training simulator to obtain the most realistic training for upcoming wells. Requirements on a high-fidelity model are in several ways more challenging in a training simulator environment than in operations, except that the consequences of failure are normally much less severe. Thus a training simulator provides a useful environment for model development.

Although the points made are relevant for automation of drilling operations in general, MPD will be used as an example in the discussion below. A number of well operations require some variant of MPD for improved downhole pressure control, and also for wells where MPD is not strictly required it has a large potential of increasing margins and reducing risk. There are however challenges related to additional cost and complexity, and due to the latter some risk elements may be aggravated.

Both challenges can be addressed by robust automation of parts of the operation, like for example automated choke response to changes in pump rate and string movements.

Accordingly, this paper is written to give input to work as outlined by sharing considerations and field experience related to using comprehensive real time models.

A note on terminology: We use the term flow model or comprehensive flow model to denote a comprehensive real-time enabled high-fidelity and (partly) dynamic mathematical model. Contrary to this, the term simplified flow model denotes a mathematical model that is less detailed and ambitious w.r.t. accurate representation of the physical system, but also less demanding when it comes to computational requirement and, due to its simplicity, it is much easier to ensure a high degree of stability and robustness.

2. PHYSICAL SYSTEM AND COMPLEX MODEL

The physical system

When trying to predict pressure effects very accurately, either to control pressure at a given measured depth or to detect anomalies early and reliable, many physical effects are significant and need to be considered in the automated system.

Normally the two most important pressure effects in drilling operations are related to changes in pump rate and axial movements of the running string. As a convenient generalization, the term running string is used to denote both drill string and completion strings.

With some exceptions not being addressed here, drilling fluids are much more viscous than pure water or oil, which is necessary to ensure sufficient ability to carry solid particles during pump stops. Due to the high viscosity rapid sound waves are quickly dampened along long wells, and the interplay between the compressibility and viscosity of the fluid is a much more predominant effect.

When both compressibility and viscosity are large, there will be a large time delay between for example changing inlet pump rate till stable return at the same level is seen at the outlet. 20-30 seconds is typical, but depends on fluid properties and the geometry of the flow trajectory. Meanwhile the change in flow is propagating through the system, as is the corresponding change in pressure. Thus, getting the timing of the process right is necessary to keep constant pressure at a given position, in addition to calculating the pressure loss vs. flow rate correctly at any position.

Moving pipe up and down, normally referred to as swab and surge respectively, causes similar flow and pressure effects as pump rate changes. A downwards pipe movement, for example, will displace fluid below bit and flow will build up gradually from bit and upwards at the same time as fluid is being compressed due to the pressure increase. The effect of geometry changes along the string may modify the effect of the pipe movement significantly. Induced flow due to surge movements may typically be of the same order as normal pump rate.

A common conception is that the major part of the pressure loss is along the BHA assembly. But normally this is not the case because the drill string is several thousand meters long, while the part of the BHA with larger diameter is less than 50 m long.

The pressure and temperature dependence of the fluid properties may be significant. With oil base drilling fluids, viscosity may increase by as much as a factor two or more when going from surface pressure to bottom hole pressure with unchanged temperature. Temperature effect is also large, and will typically cancel some of the pressure effect. With water base drilling fluids the temperature effect is still large, but pressure effect much smaller. This may cause significant effects, and in addition to the prediction of a complex process there may be a proprietary issue in getting the most accurate fluid properties data.

High-fidelity mathematical models

The effects above are taken into account by state of art dynamic models, which will normally give a fairly accurate picture provided relevant input parameters are given with sufficient accuracy. See for example Bjørkevoll et al (2009) and a large number of SPE papers on the subject. The latter is not always the case, and will be discussed further below.

Other physical effects worth considering include changes in temperature profile and cuttings transport, which both are important parameters in themselves, and may influence downhole pressure significantly. Current models include dynamic temperature calculations, although its dependence on a large number of parameters makes accurate prediction under drilling conditions difficult and uncertain. Accurate cuttings transport modelling is still a challenge after decades of work in this field.

Working with mathematical models

In order to succeed, taking steps to develop models that are both accurate and at the same time fit for real time purposes has to be acknowledged as a most challenging process where a number of elements need to be progressed to a high level of quality to succeed. The sketch in Figure 1 shows how some main elements are linked and what they contain.

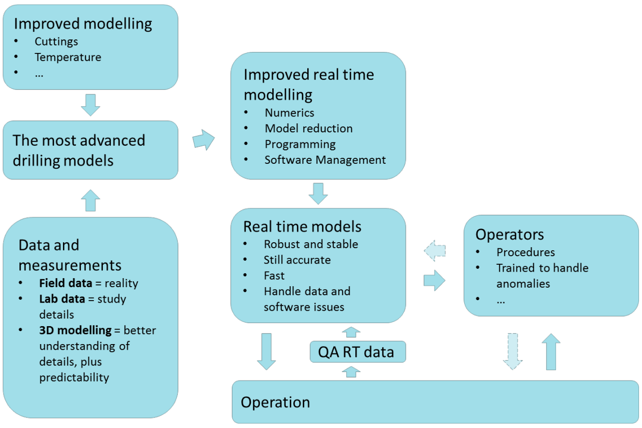

Fig. 1. Working with mathematical models to obtain *safer and faster operations.*

In the left hand column focus is kept on modelling the process as accurately as possible. A combination of solving basic physical equations with measurements and data analysis is used, and the level of accuracy obtained will depend what is state of art for modelling of the process being addressed. Here accuracy and predictability is the main focus. Calculation speed and stability are of course of importance, but play a more secondary role at this stage.

Going from the left to the middle column is about reducing and possibly reprogramming the accurate models while striving to maintain a sufficient degree of accuracy. At the same time the main goal is to obtain a mathematical model that is useful for decision support or for giving input to automated loops, where very high requirements to regularity and calculation speed have to be met.

The right column puts in the human operator, who in some cases may just monitor and only intervene in case of something going unexpectedly wrong. In other cases there will be planned operator interaction with the system (shown by dashed arrows in the figure), either regularly or under given conditions.

Level of interaction will typically be large at early stages of new technology, with a goal of reducing it as the system becomes mature and sufficient trust has been gained. As time and cost are very high in drilling operations, aiming for a system that does not add time or personnel to the operation will be a normal goal, and also a stronger goal involving quicker operations and fewer personnel should be considered and attempted built into the implementation plan. A more detailed description of the role of human operators is given below.

3. BENEFITS

This section goes into details on some main advantages of running real-time models during operations. Quick changes can be handled by a simplified model which is very fast and robust, and may be closely integrated with the control loop. The first items below are partly in this category. However, running without any sensor for longer intervals and under changing conditions will require a model with higher degree of predictability based on first principles.

A. Filling in gaps between sensors in time and space may be important to get a sufficiently complete picture of the situation in the well. The calibrated models may be used to get accurate profiles between sensors, taking into account discontinuities like changes of geometry and multiple fluids. This is most important when sensors are far from where pressure margins are narrowest, which for example may happen in long open hole sections with sensors located in bottom hole assembly (BHA) only.

   Furthermore, models can also be used to improve results when sensor data are delayed, by calculating effects of operational changes before the response shows up on measurements. With commonly used mud pulse telemetry, time delay of 30 seconds is quite normal, while mathematical models can respond to changes in one second or less.

   An even larger delay, or rather lack of data, occurs during pump stops when using mud pulse telemetry, because data transition stops as soon pump rate gets below a given threshold. Even with a real time model this may be challenging because data for model calibration is limited or absent. And this also challenges the robustness of control algorithms, refer for example Siahaan et al (2014) for details.

B. When a comprehensive model has been used and accurately calibrated in the preceding drilling run, it can be taken further to the following casing, liner or other completion string run to provide synthetic "sensors" in the open hole. This is valuable because there are normally no downhole sensors in such runs, and the operation is therefore a challenge if narrow pressure conditions have been confirmed when drilling.

C. Add redundancy to automatic systems. If sensors fall out, a calibrated real time model can take over and give input corresponding to the missing sensor data to the control system.

D. Improve understanding of well status, for example by combining model calculations with sensor data and multivariate techniques to obtain early and reliable detection of anomalies like kick, loss, poor hole cleaning, etc.

   This point is far from trivial and still a topic for further research, because deviation between a model and measurements may have a number of different causes that can be very hard to separate. Causes include inaccurate model input data, inaccurate sensors and leakages in addition to the various well anomalies mentioned above.

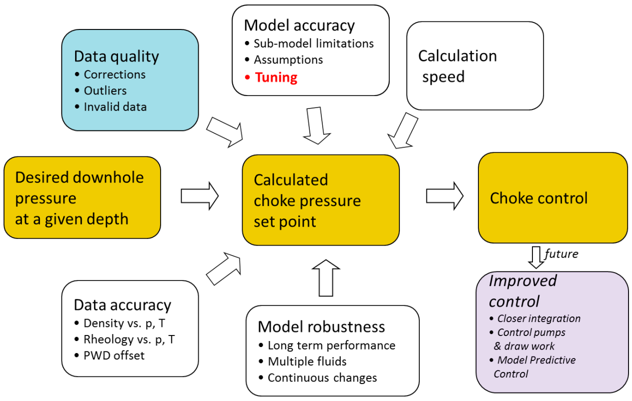

Fig. 2. Important factors influencing performance of a model based system.

CHALLENGES / ROBUST IMPLEMENTATION

Realizing the potential benefits listed above is only possible if the implementation is done in a robust way, such that challenges are handled adequately. Figure 2 shows factors that are important to obtain the required accuracy of pressure control in MPD, and the following discussion goes into details on some of these.

The MPD operations done included a number of operator actions, some part of regular procedures and some included as contingency measures. Some tasks require good training and careful attention, and should therefore be subject for improved user interface and robust automation as far as possible.

Manual operator actions have included:

- Collect input data and feed into the model, including things like well geometry, survey data, running string with bottom hole assembly, fluid properties, formation layers, water depth, etc.
    - Testing model responses prior to start of operations.
- Update configuration with new information, including
    - BHA specification between runs.
    - Survey data between runs and a few times during runs, according to considerations.
    - Manual update of fluid density. Typically each 15 minutes at best while drilling.
    - Manual update of rheology at standard conditions. Typically up to 4 times per day while drilling. Good communication with mud engineer is important to avoid significant time delays.
- Handle deviations between model and measurements.
    - Tuning of the model to match downhole data, provided considered trustworthy. This point will be elaborated on below, under data quality and tuning.
- Monitor the model and transfer to manual control in the case of model failing or getting instable. A robust procedure must be in place for this event. Examples seen include:
    - Abrupt operational changes causing oscillations in choke system.
    - Internal model issues. A number of issues have been seen over the eight wells drilling with the high-fidelity model in the loop, and after a number of appropriate fixes severe issues are now very rare. But still not ruled completely out, and therefore further work on robustness and stability is ongoing and recommended.
    - Hardware issues. In one case instable model behaviour was remedied by simply replacing the computer.

Tuning of models

Accurate and robust model tuning is crucial to correct offsets between model and data that are due to model or input data being inaccurate. If there is an offset due to well anomalies, tuning of model may still work, but now the model becomes less predictive because it does not represent important features of the physical system. And also a detection of the anomaly will be valuable if the system is able to distinguish between different causes of deviation between data and model. A further discussion of this topic is given in Bjørkevoll et al (2015).

Data quality issues

The data quality issues seen when working with real time models have turned out to be a much larger challenge than expected initially, and make both manual and automatic interpretation and automation hard. Based on experience this has been addressed two ways; firstly by improvements of sensors and signal transmission, and secondly by adding data quality checks and corrections between sensor data and models.

Even topside sensors have turned out to be less accurate and more time delayed than desired, and steps have been taken to improve these things. When it comes to downhole sensors significant drifting has been seen and must be considered when choosing sensors and interpreting measurements.

The fact that transmission by mud pulse telemetry stops during connections is to some extent remedied by sending minimum and maximum pressures during connection after pumps have started again. These measurements are useful for understanding whether calculated static pressure is accurate.

If data is only available when pumping at high rate it will be hard or impossible to distinguish contributions from static pressure and pressure drops due to fluid flow.

However, cases have been seen where the static pressure is inconsistent with real time pressure while pumping, as shown by jumps in Figure 3. The pink dots show minimum and maximum values transferred after connection, and the full curve including the two jumps and curve in between were only available from the tool memory after the full run.

Another example is shown by Figure 4. In this case minimum and maximum values were correct, but an interpretation based on only the two values was very difficult. Seeing the whole curve and comparing with other parameters it was possible to deduce that the largest pressure variations were related to time delays.

Figure 5 illustrates another challenge. In this case the model ran with inaccurate rheology input data for more than two days. With good training and communication this can be reduced a lot, but still it shows potential vulnerability and also potential benefit of an integrated system with robust and automatic update of fluid properties. Similar challenges have been seen due to inaccurate fluid density values, in particular when displacing to a new fluid.

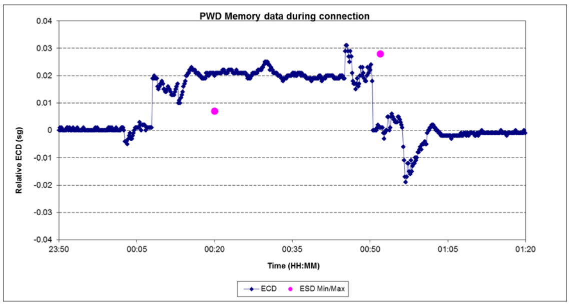

Fig. 3. Memory recorded downhole pressure during connection.

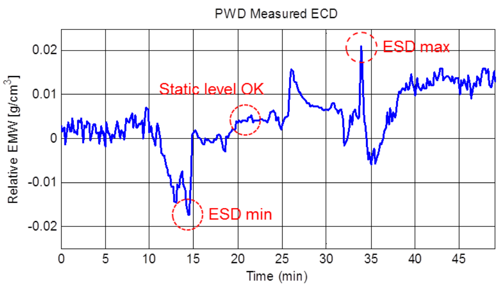

Fig. 4. Memory recorded downhole pressure during connection.

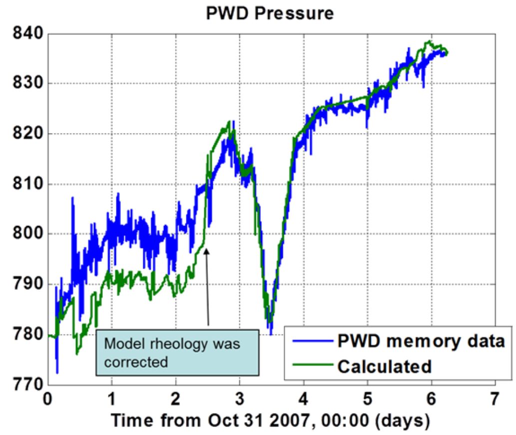

Fig. 5. Measured and calculated downhole pressure over 6 days of drilling, including a short trip up to the casing shoe.

A FINAL REMARK

The MPD operations referred to were all concluded successfully by combining all involved resources and addressing challenges in the extended drilling team. Issues and anomalies were handled by good procedures, communication and judgements. Accordingly, it is appropriate to include the sequence of washing down a few stands shown by Figures 6-8, where everything worked well. Further improvements might be possible in this case by advanced model predictive control, but then again robustness is important, and things like unexpected loss of pump power must be handled according to requirements.

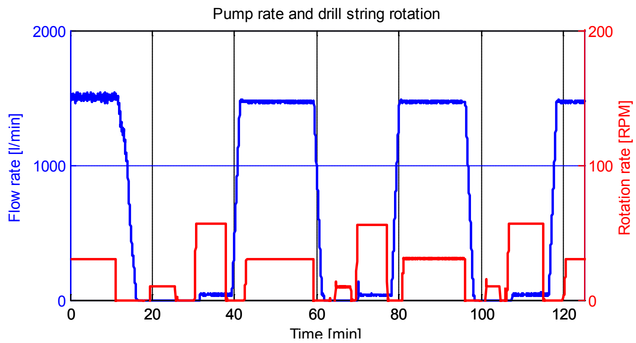

Fig. 6. Pump rate and drill string rotation during a run in hole sequence; copied from SPE/IADC 130311.

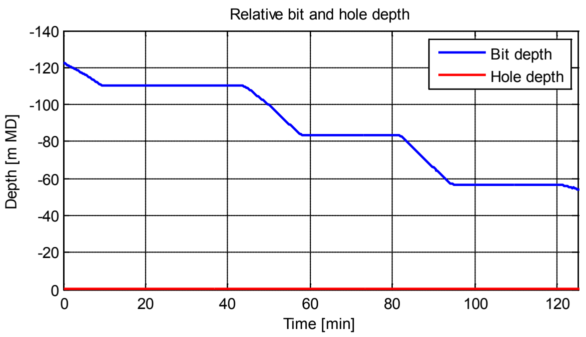

Fig. 7. Bit and hole depth; same sequence as Fig. 6.

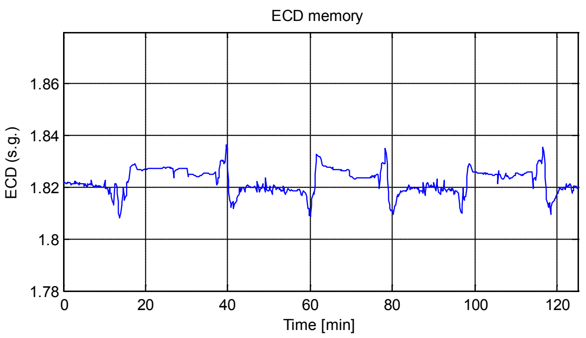

Fig. 8. Measured downhole pressure converted to equivalent mud weight; same sequence as Fig. 6.

REFERENCES

Bjørkevoll, K. S., Molde, D. O., Rommetveit, R., Syltøy, S. (2008). MPD Operation Solved Drilling Challenges in a Severely Depleted HP/HT Reservoir. SPE 112739, SPE/IADC Drilling Conference, Orlando, Florida, 4-6 March 2008.

Bjørkevoll, K. S. (2009). Design Considerations for High-Pressure/High-Temperature Well. Book chapter in "Advanced Drilling and Well Technology", p.641-675, Society of Petroleum Engineers.

Bjørkevoll, K. S., Hovland, S., Aas, I. B., and Vollen, E. (2010). Successful Use of Real Time Dynamic Flow Modelling to Control a Very Challenging Managed Pressure Drilling Operation in the North Sea. SPE 130311, presented at the SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition in Kuala Lumpur, 24-25 February 2010.

Bjørkevoll, K. S., Daireaux, B., Manum, H. (2015). Possibilities, Limitations and Pitfalls in Using Real-Time Well Flow Models During Drilling Operations. To be presented at the SPE Bergen One Day Seminar in Bergen, Norway, 22 April 2015.

Gjerstad, K., Time, R. W., Bjørkevoll, K. S. (2012). Simplified explicit flow equations for Bingham plastics in Couette–Poiseuille flow – For dynamic surge and swab modelling. Journal of Non-Newtonian Fluid Mechanics 175-176 (2012) 55–63.

Rommetveit, R., Ødegård, S. I., Bjørkevoll, K. S., Herbert, M. (2009) Testing a new software system for drilling supervision. *World Oil 230 (4), 47-52.*

Siahaan, H. B., Bjørkevoll, K. S., Gravdal, J. E. (2014). Possibilities of Using Wired Drill Pipe Telemetry During Managed Pressure Drilling in Extended Reach Wells. SPE 167856, SPE Intelligent Energy Conference and Exhibition, Nederland, 1-3 April 2014 - Conference Proceedings. Society of Petroleum Engineers 2014 ISBN 978-1-61399-306-4. s. – SINTEF Petroleum and IRIS.

Syltøy, S., Eide, S. E., Torvund, S., Berg, P. C., Larsen, T., Fjeldberg, H., Bjørkevoll, K. S., McCaskill, J., Probensen, O. I., Low, E. (2008). Highly Advanced Multi-Technical MPD Concept Extends Achievable HPHT Targets in the North Sea. *Conference paper SPE 114484, presented at the 2008 SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition in Abu Dhabi, UAE, 28–29 January 2008.*