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Supervisory control for underbalanced drilling operations

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Abstract: Good flow and pressure control is essential for successful Underbalanced Drilling (UBD) operations. This work evaluates the use of Model Predictive Control (MPC) for integrated control of well conditions and the topside separation system during UBD. The downhole well pressure, separator liquid levels, and the separator pressure are controlled by manipulation of the rig pump, the choke, and the separator valves. The control system adheres to downhole and topside constraints. These constraints include pore and collapse pressures, minimum flow rate for hole cleaning, maximum choke pressure, separator pressure, and separator liquid levels. The proposed MPC solution uses simple Hammerstein-Wiener models, where parameters are determined by system identification incorporated into standard drilling procedures. The control system is tested using a high-fidelity multi-phase flow simulator (OLGA) for some common drilling scenarios, including drilling into a producing formation and performing connections. We show that the MPC solution is able to take proactive action to ensure safe and efficient operation without having to enter well control mode or shutting down the separator system. By limiting the amount and variation in influx from the reservoir, we get less Non-Productive Time (NPT), we improve safety, and we may to some extent be able to reduce the footprint of the equipment.

Keywords: Process control, model predictive control, simulation, drilling automation, multi-phase flow, underbalanced drilling

1. INTRODUCTION

Drilling is one of the oldest engineering activities in the world, yet the current degree of automation is still surprisingly low. The authors have been involved in many discussions about why this is so, and the commonly stated reasons include: the companies do not see the added benefits; the safety requirements are too stringent; the available sensors are not good enough; retro-fitting of rigs is too expensive; and the all too common, it is too hard to change the existing practices.

However, due to ever rising drilling costs and new safety concerns, we see renewed interest in improved automation solutions for drilling. We are still a long way from commonly accepted industry standards and easily implementable systems (Saeed et al., 2012), but we now see a more systematic discussion of how the process can be automated, and which levels of control are most suitable for drilling (Godhavn, 2009; Breyholtz and Nikolaou, 2012; Macpherson et al., 2013).

There are several interesting control challenges within the field of drilling, such as: vibration management, directional drilling (geo-steering), automatic fluid mixing, and automatic pipe handling. However, we limit this article to the area of flow and pressure control. Flow and pressure control are instrumental to the stability, safety, and successful drilling of a well. The nightmare scenario during any drilling operation is that a severe gas kick, an uncontrolled influx of gas, evolves into a full blow-out and potentially another Macondo accident. This is a possible scenario if a kick is not detected early enough, or if insufficient actions are taken. Secondary concerns are: having to abandon a two-hundred million dollar well because the reservoir was badly damaged or the well collapsed; or having to perform expensive side-track operations.

The normal mode of operation in most drilling operations is to be statically overbalanced. By overbalanced, we mean that we always have a higher pressure in the part of the well exposed to the reservoir, than exerted by the reservoir. By static, we here mean when not circulating any fluid. If this is achieved we have no influx of reservoir fluids (including gas) when drilling. Drilling rigs are generally not equipped to process large amounts of reservoir fluids.

We can be overbalanced by adjusting the density of the mud; or if the well is sealed with a Rotating Control Device (RCD) a backpressure can be enforced at the surface by manipulation of the choke. Note that we need some flow through the choke to be able to control the pressure.

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Operations where we use a controlled backpressure is one type of Managed Pressure Drilling (MPD). The flow rate will affect the pressure in the well due to the frictional pressure drop in the annulus. We have a steady state, fundamental equation for the bottomhole pressure (Rehm et al., 2008):

$$p_{\mathrm{bh}} = p_{\mathrm{hydr}} + p_{\mathrm{afp}} + p_{\mathrm{bp}}, \tag{1}$$

where p_{hydr} is the hydrostatic pressure exerted by the drilling fluid and the cuttings load, p_{afp} is the annulus friction pressure loss, and p_{bp} is the applied back-pressure.

The International Association of Drilling Contractors (IADC) has defined Underbalanced Drilling (UBD) as: "A drilling activity employing appropriate equipment and controls where the pressure exerted in the wellbore is intentionally less than the pore pressure in any part of the exposed formations with the intention of bringing formation fluids to the surface" (IADC, 2011).

UBD is often considered more complex than conventional drilling or MPD due to the presence of multi-phase fluids, the need for additional equipment and procedures, the lack of customized rigs, and the additional crew and training required during the drilling operations; and sometimes it is simply not technically feasible. However, we know that in some cases the economic gains are high enough that UBD is the preferred choice, and in some cases it is the only choice (Finley et al., 2006). Note that in MPD the pressure window is between the pore pressure and the fracture pressure, while in UBD it is between the collapse pressure and the pore pressure. In some situations the size of the windows will determine the appropriate technique. We limit the discussion in this article to UBD systems where we have injection of a lightened fluid, and disregard e.g. foam, air and mist systems.

If we examine Eq. 1, we can see that the term p_{hydr}, which in overbalanced drilling is determined by the combined density of the drilling fluid and the cuttings load, and the height of the fluid column, now will depend on the amount of reservoir fluid and injected lighter fluid in the annulus. The pressure loss, p_{afp}, will also depend on the reservoir influx, as the influx will change the friction parameters and the magnitude of the flow in the annulus. The reservoir influx depends on the pressure differential in the openhole region (i.e. the pressure differential between the reservoir pressure and the bottomhole pressure) and the reservoir productivity index. We therefore have a natural feedback loop with several steady-state solutions. See Aarsnes et al. (2014a) for a treatment of the problem.

It should be noted that in the case of MPD we only have relatively fast dynamics, as changes in choke openings and pump flow travel with the speed of sound, meaning that changes will be seen at the bottom in seconds or tens of seconds. In UBD we also have the much slower gas transport dynamics, which may take a very long time to converge, typically tens of minutes.

Fig. 1 shows a simplified schematic of the system. The well is shown as a u to illustrate the coupling of pressures at the bottom. It should be noted that the drill-pipe is duplicated on the right-hand side to illustrate that the return path is not a simple pipe, but modelled as concentric annuli. This is of course a drastic simplification, since the drill-pipe will be moving, we have several eccentricities in the annulus, the wellbore wall is uneven (and unknown), and the well geometry will cause the pipe to move away from the centre. There is a Non-Return Valve (NRV) in the drillstring which means that there will be no backflow into the string. The drill-bit is shown as a valve, to indicate that we have a large pressure loss over the nozzles. Note that the figure does not show the location of measurements.

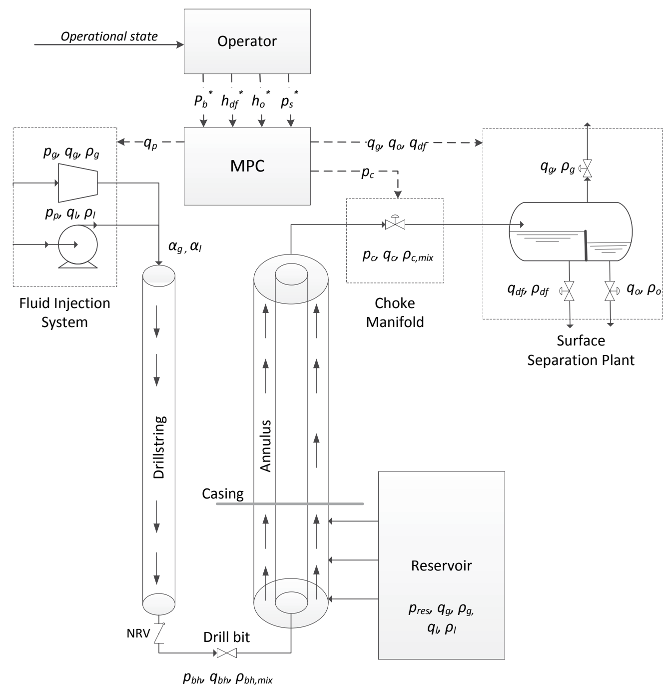

Fig. 1. Simple schematic of the well and the topside equipment.

We already mentioned measurements as an issue of concern. In drilling we have a strong separation between downhole measurements and topside measurements. Topside measurements are usually available, or could be made available. They are (compared to the process dynamics) frequent, and usually of decent quality. However, for bottomhole measurements the most common method for sending data to surface is referred to as mud-pulse telemetry. This is a technique where pressure pulses are modulated through the drilling mud. The process is slow, a bit-rate of 5-10 bits per second is not uncommon, it has long delays and is noisy (Downton, 2012). We will also lose all downhole measurements during connections (and other scenarios with no or low circulation) or if we have too much gas in the drillstring. It is, however, possible to send the data to the surface after circulation is restored. Better systems, such as wired drill pipe (WDP), are available. WDP offers communication delays of as little as 2-4 seconds with high-speed data transmissions. However these systems have only been used in maybe a few hundred wells, and many of these were pilot projects (Pixton et al., 2014). This number is vanishingly small, as the estimated number of active oil and gas wells in the US alone are more than one million (Note that this is also true for MPD wells and to some extent UBD wells). WDP is still perceived as an immature technology and as a costly investment by the general petroleum industry. For a general discussion