Multi-objective Optimization of an Oil Well Drilling Process for Safe Process Operation

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Oil well drilling multi-criterion dynamic optimization analysis was carried out through simulation and experimental studies. Schemes including drilling rate, choke valve opening index, pump circulation rate (input variables) were employed to evaluate the process performance (annulus bottom hole pressure – drilling inside operational window and annulus solid concentration – maximizing drilling rate).

1. Introduction

A drilling system consists of a rotating drill string, which is placed into the well (Fig. 1). The drill fluid is pumped through the drill string and exits through the choke valve. An important scope of the drill fluid is to maintain a certain pressure gradient along the length of the well. During drilling, disturbances that produce fluctuations in the well pressure might occur. As the well is drilled, the hydrostatic pressure increases because of the well length grow. In addition, the reservoir fluid influx changes the well flow rate and density of the well fluid mixture. Finally, the pipe connection procedure, which requires stopping and starting of the drill fluid, produces severe fluctuations in the well flow rates. The pressure balance between the well section and the reservoir is important. If the pressure in the well is higher than the reservoir pressure, it is referred to as over-balanced drilling. This condition causes the circulation fluids to penetrate into the reservoir formation. On the other hand, if the pressure in the well is lower than the reservoir pressure, it is referred to as under-balanced drilling, and the reservoir fluids migrate into the well annulus. Over-balanced drilling is the most used method for drilling oil wells. The reason for this is that it nearly eliminates the risk for an uncontrolled ‘‘blow-out’’ situation, where the pressure in the reservoir causes large amounts of the reservoir fluids to penetrate into the well and follow the well to the surface. Today, different type of equipment such as blow-out preventers, gives the possibility of reducing the well pressure lower than the reservoir pressure (Nygaard et al., 2006).

An optimization analysis of a drilling process constitutes a powerful tool for operating under desired pressure levels and simultaneously maximizing the penetration rate, which reduces costs, as oil derrick operation demands around U$220,000.00/day. The procedure traditionally adopted in optimization studies is the formulation of a single objective function combining all performance measurements with weighting functions chosen a priori. The a priori choice of weights do not successfully demonstrates which optimum trajectory the manipulated variable should follow for dealing with conflicting objectives; in addition, there are no evidences that the specific use of certain manipulated variables will produce superior quality results.

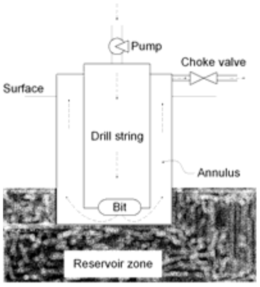

Figure 1 – Oil well drilling scheme.

Wang et al. (2000) pointed out that traditional mathematical programming algorithms use two strategies for solving optimization problems: single objective optimization, using the others objectives as constraints; and the altogether objectives optimization, using weighting factors. For the second approach, the arbitrary choose of weights and the diverse quantities unification (cost, product quality, environmental effects) in a common measure produce criticism. Besides, the second strategy is not able to find the optimal solution for a non convex objective function. The majority of real-world problems present complex nature and conflicting objectives, being rarely convex. Therefore, a judicious solution of optimization problems requires the use of multi-criterion approach, producing a family of solutions named optimum Pareto set. As a result, the multi-objective optimization, which seeks to harmonize conflicting objectives, appears as an interesting approach, being also called as efficient or multi-criterion optimization. The solutions are named Pareto optimum, maxima vector, efficient points, non inferior solutions or non dominant solutions.

The major objective of this paper is applying multi-criterion dynamic optimization to an oil well drilling process through simulation and experimental studies. The presence of conflicting objectives was identified, that is, an objective function could not be improved without sacrificing the other. Pareto optimization (ε-constraint method) is implemented by initializing the optimization algorithm with distinct initial guesses, for attaining global optimum, according to the methodology of Madsen (2000). Various schemes were analyzed, including drilling rate, choke valve opening index, pump circulation rate (input variables) in order to evaluate the process performance (annulus bottom hole pressure and annulus solid concentration).

2. Pareto optimization

There are several methods described in the literature about the Pareto set generation (Chankong et al., 1983). They basically transform the original multi-objective problem into many single objective optimization related problems. The transformation is done under conditions that guarantee the construction of the Pareto set. Also this transformation enables a numerical solution for the original multi-objective problem.

The simplest and the most usually applied technique is the ε-constraint approach (Tsoukas et al., 1982). In this method, one of the objective functions of the original multi-objective optimization problem is selected to be the single objective function (primordial objective function), while the others are included as constraints. These new constraints are subjected to maximum values previously chosen. Therefore the ε-constraint approach transforms the multi-objective optimization problem, Eq. (1), composed by N objective functions, into a single objective optimization problem described by Eq. (2).

$$\min F\{x(t_f), t_f\} = [F_1(x, t_f), F_2(x, t_f), \cdots, F_N(x, t_f)] \tag{1}$$

System constraints: $\begin{cases} \dot{x} = l(x, u) \\ x(0) = x_0 \end{cases}$ Manipulated variables constraints: $h[u(t)] \le 0$

End point constraints: $g[x(t_f)] \le 0$

$$\begin{aligned} &\min F_1(u) \\ &\dot{x} = l(x, u) \\ &x(0) = x_0 \\ &F_j(u) \le \varepsilon_j, \quad j = 2,3,\cdots,N \\ &u \in \Omega \end{aligned} \tag{2}$$

3. Experimental unit

An experimental unit was built in order to represent the situations commonly observed in oil well drilling: tracking of the annulus bottom-hole pressure set point for respecting operational windows and rejection of density perturbation, as the improvement of the drilling rate increases solid concentration. Further details of the experimental unit, describing oil well drilling process, may be found elsewhere (Vieira, 2009). Experimental optimization tests were performed based on simulation results found by Vega et al. (2008).

4. Results and discussion

Details of the mathematical model describing oil well drilling process may be found elsewhere (Vega et al., 2008). The annulus bottom hole pressure was defined as the summation of annulus compression and hydrostatic pressures, frictional losses, pressure loss over the choke and atmospheric pressure. The state vector for the drilling problem includes liquid, gas and solid masses inside the drill string; liquid, gas and solid masses inside the annulus; well length; mass flow of the mixture at the bit and mass flow of the mixture at the choke, Eq. (3). The set of time varying control inputs (manipulated variables: drilling rate, choke opening index, pump flow) to the process are shown in Eq. (4).

$$x(t) = \left[m_{gd}, m_{ld}, m_{sd}, m_{ga}, m_{la}, m_{sa}, L, W_{mix,bit}, W_{mix,choke} \right] \tag{3}$$

$$u(t) = [vd, zchoke, wpump] \tag{4}$$

To apply the multi objective optimization method to the oil well drilling problem, two objective functions were selected for being minimized, as can be observed from Eqs. (5-6). Maximizing annulus solid mass produces the effect of maximizing the rate of penetration into the well, reducing the drilling cost. Concerning the second objective function, the aim was increasing the annulus bottom hole pressure to a desired level named $Pabotd$. The complex situation where narrow operational window between pore and fracture pressures occurs, mainly when lower collapse is higher than pore pressures and/or upper collapse is lower than fracture pressures, was taken into account by including this variables as nonlinear constraints into the optimization problem.

$$F_1[x(tf), tf] = [1/(1 + m_{sa})] \tag{5}$$

$$F_2[x(tf), tf] = [(Pabotd - Pabot)/Pabotd]^2 \tag{6}$$

For the multi objective optimization problem, the primordial objective function was maximizing the rate of penetration. The other objective function (minimizing mud invasion into the reservoir or migration of reservoir fluids into the well annulus) is included as a nonlinear constraint. During oil well drilling, the pore pressure (minimum limit) and the fracture pressure (maximum limit) define mud density range. As a result, the drilling fluid hydrostatic pressure needs to be higher than pore pressure, in order to avoid formation fluid invasion into the well. Simultaneously, the drilling fluid hydrostatic pressure needs to be smaller than fracture pressure, for avoiding formation damage.

As can be observed from Fig. 2, two different control modes are illustrated: drilling rate (vd) and choke opening index $(zchoke)$ versus drilling rate (vd) and pump flow $(Wpump)$. For the two objectives chosen, the theoretical absolute minima are $F_1^{min} = 0$ and $F_2^{min} = 0$. This point is termed utopia point. It can be observed that there is a trajectory (drilling rate and pump flow inputs) which gives the closes approach to utopia, an in fact, requires very little sacrifice of the objective function F_2.

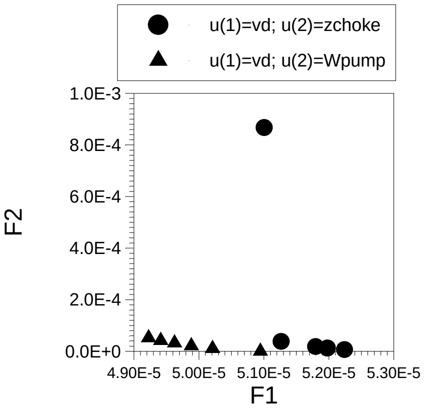

Figure 2 – Pareto set - simulation result.

The Pareto optimization strategy unveiled that drilling rate and pump flow were the most appropriate input variables in order to maximize the rate of penetration (annulus solid concentration) and to drill under desired pressure operational window (minimize mud invasion into the formation and migration of reservoir fluids into the well annulus). These optimization results were implemented at the experimental unit using water (Figure 3) and mud (Figure 4), as drilling fluids, in order to produce low and high annulus solid concentration, respectively. As can be observed from Figs 3 and 4, representing oil well drilling inside a desired operational window, the use of pump flow rate, as input variable, is preferred versus choke opening index for making operation under high solid concentration feasible. Concerning the optimization analysis, it can be observed that the use of pump flow, as an input variable, affect annulus bottom hole pressure through changes of frictional losses and solid concentration, as alters solid residence time into the well. The use of choke opening index impacts annulus bottom hole pressure through the pressure drop produced by valve restriction; otherwise, has no cleaning action, for positive displacement pump imposes constant solid residence time, no matter the choke valve position.

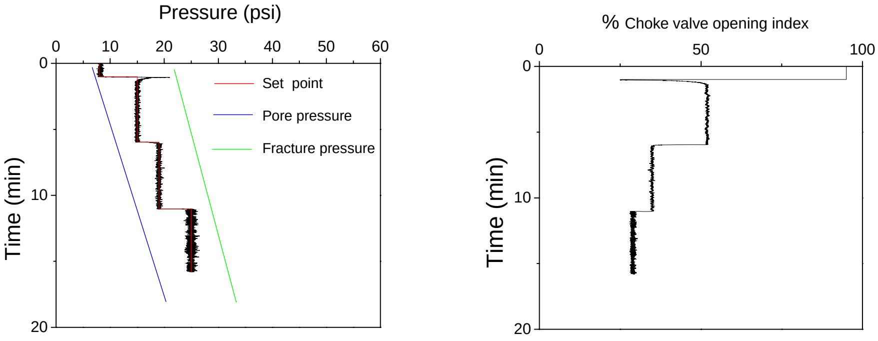

Figure 3 – Optimization test using water as the drilling fluid – experimental result

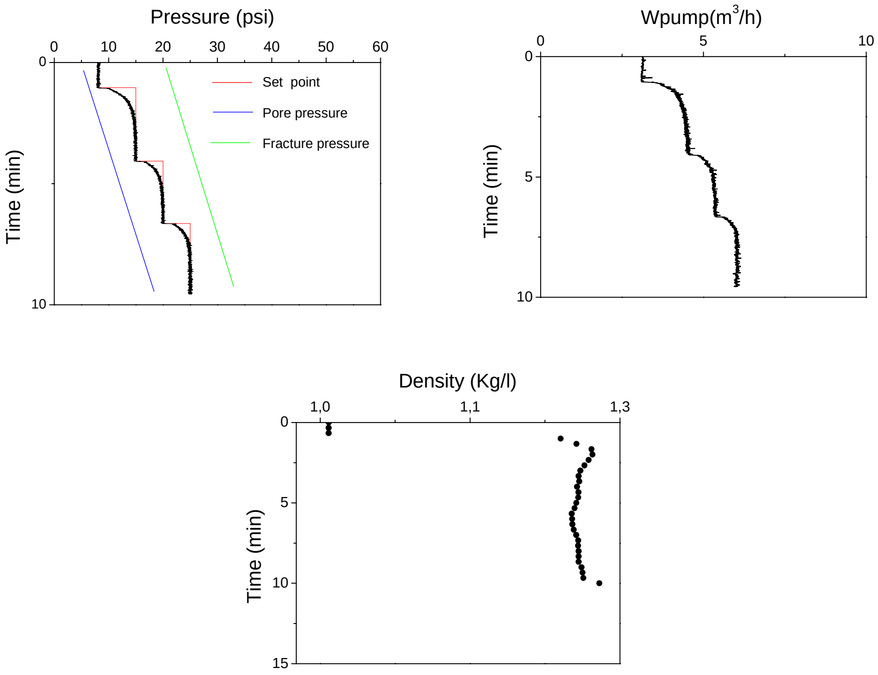

Figure 4 – Optimization test using mud as the drilling fluid – experimental result

5. Conclusions

The Pareto optimization strategy unveiled that drilling rate and pump flow were the most appropriate input variables in order to maximize the rate of penetration (annulus solid concentration) and to drill under desired pressure operational window (minimize mud invasion into the formation and migration of reservoir fluids into the well annulus).

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