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Estimation of States and Parameters of a Drift-Flux Model with Unscented Kalman Filter

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Abstract: We present a simplified drift-flux model (DFM) describing a multiphase (gas-liquid) flow during drilling. The DFM uses a specific slip law, without flow-regime predictions, which allows for transition between single and two phase flows. With this model, we design an Unscented Kalman Filter (UKF) for estimation of unmeasured states, production parameters and slip parameters using real time measurements of the bottom-hole pressure and liquid and gas rate at the outlet. The performance is tested against the Extended Kalman Filter (EKF) by using OLGA simulations of typical drilling scenarios. The results show that both UKF and EKF are capable of identifying the production constants of gas from the reservoir into the well, while the UKF has better convergence rate compared with EKF.

Keywords: Under-balanced drilling, UKF, Adaptive observer, simplified drift-flux model.

1. INTRODUCTION

There have been an increasing research focus on automation of drilling for exploration and production of hydrocarbons in the recent years. Modeling for estimation, and model-based control techniques have been studied in a wide range of drilling and production scenarios. In Managed Pressure Drilling (MPD), a back-pressure pump in conjunction with a back pressure choke is used to control the pressure in the well, posing new control and estimation challenges. In a typical scenario, the control goal is to keep the pressure of the well ($p_{\text{well}}(t,x)$) greater than pressure of the reservoir ($p_{\text{res}}(t,x)$) to prevent influx from entering the well, but lower than the fracture pressure ($p_{\text{frac}}(t,x)$) to avoid the loss of drilling fluids to the reservoir

$$p_{\text{res}}(t,x) < p_{\text{well}}(t,x) < p_{\text{frac}}(t,x) \tag{1}$$

at all times t and along the well profile $x \in [0, L]$.

In an alternative approach, known as Under-Balanced Drilling (UBD), the pressure in the well is kept greater than the collapse pressure of the well but lower than the pressure of the reservoir

$$p_{\text{coll}}(t,x) < p_{\text{well}}(t,x) < p_{\text{res}}(t,x) \tag{2}$$

Due to the pressure drawdown (meaning the positive difference of the reservoir pressure and well pressure) inflow fluid, in many cases gas, is produced continuously from the reservoir. The rate of reservoir inflow is typically approximated mathematically by a so-called Production Index (PI) parameter

$$q_{influx} = \text{PI}.\max(p_{\text{res}} - p_{\text{bh}}, 0). \tag{3}$$

Especially for under-balanced wells producing gas, the magnitude of the PI has a significant impact on the dynamics of the UBD and thus also on the control problem. Hence, accurate estimates of the PI and reservoir pressure are important for an UBD operation.

Modeling of UBD operations and MPD scenarios handling influx requires a multiphase model. A popular model in the literature is the Drift-Flux Model (DFM) Evje and Fjelde (2002); Lorentzen et al. (2003); Lage et al. (1999). The drift flux model is a set of first order nonlinear hyperbolic partial differential equations (PDE). In case of two-phase flow, it consists of three governing equations. The Low-Order Lumped (LOL) models are simpler methods that can be used. However, these models are only able to capture the major effects in the well and for the general purpose it produces less accurate results. Nygaard and Nævdal (2006); Nikoofard et al. (2014a); Storkaas et al. (2003).

Due to the complexity of the multi-phase flow dynamics of a UBD well coupled with a reservoir, the modeling, estimation and model based control of UBD operations is still considered an emerging and challenging topic within drilling automation. Nygaard et al. (2006) compared and evaluated the performance of the extended Kalman filter, the ensemble Kalman filter and the unscented Kalman filter based on a low order model to estimate the states and the PI in UBD operation. In Nygaard et al. (2007), a finite horizon nonlinear model predictive control in com-

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bination with an unscented Kalman filter was designed for controlling the bottom-hole pressure based on a low order model developed in Nygaard and Nævdal (2006).The unscented Kalman filter was used to estimate the states, and the friction and choke coefficients. Nikoofard et al. (2014a) designed a Lyapunov-based adaptive observer, a recursive least squares estimation and a joint unscented Kalman filter based on a low-order lumped model to estimate states and parameters during UBD operations. A Nonlinear Moving Horizon Observer based on a low-order lumped model was designed for estimating the total mass of gas and liquid in the annulus and geological properties of the reservoir during UBD operation in Nikoofard et al. (2014b).

Lorentzen et al. (2003) designed an ensemble Kalman filter based on the drift-flux model to tune the uncertain parameters of a two-phase flow model in the UBD operation. Vefring et al. (2003, 2006) compared and evaluated the performance of the ensemble Kalman filter and an off-line nonlinear least squares technique utilizing the Levenberg-Marquardt optimization algorithm to estimate reservoir pore pressure and reservoir permeability during UBD while performing an excitation of the bottom-hole pressure. Both methods are capable of identifying the reservoir pore pressure and reservoir permeability. Aarsnes et al. (2014a) used a simplified drift-flux model and an Extended Kalman Filter to estimate the states and PI online, and suggested a scheme combining this with offline calibration using the algorithm in Vefring et al. (2003). The provided analysis also suggests how such an scheme fits into the UBD operating envelope as proposed by Graham and Culen (2004), and explored in Aarsnes et al. (2014b). Di Meglio et al. (2014) designed an adaptive observer on the DFM.

The problem of parameter estimation in multiphase flows is often referred to as 'soft-sensing' in the context of production, see Luo et al. (2014); Lorentzen et al. (2014); Bloemen et al. (2006); Teixeira et al. (2014); Gryzlov (2011).

The unscented Kalman filter (UKF) has been shown to typically have a better performance than other Kalman filter techniques for nonlinear system (Simon (2006); Wan and van der Merwe (2002)). This paper is the first case of UKF being used with the drift-flux model. This paper presents the design of a UKF based on a simplified drift-flux model to estimate the states, geological properties of the reservoir and slip parameters during UBD operation. The performance of UKF is evaluated against EKF by using measurements from OLGA simulator and the consequences of not estimating slip parameters are discussed.

This paper is organized as follows: Section 2 presents the simplified drift-flux model based on mass and momentum balances for UBD operation. Section 3 and 4 explain UKF and EKF for simultaneously estimating the states and parameters of a simplified drift-flux model from OLGA simulator measurements. In the section 5, the simulation results are provided for state and parameter estimation. At the end the conclusion of the paper are presented.

2. THE DRIFT FLUX MODEL

The model employed is the same as the one used in Aarsnes et al. (2014b). It expresses the mass conservation law for the gas and the liquid separately, and a combined momentum equation. The mud, oil and water are lumped into one single liquid phase. In developing the model, the following mass variables are used

$$m = \alpha_L \rho_L, \qquad n = \alpha_G \rho_G$$

where for $k = L, G$ denoting liquid or gas, ρ_k is the phase density, and α_k is the volume fraction satisfying

$$\alpha_L + \alpha_G = 1. \tag{4}$$

Further v_k denotes the velocities, and P the pressure. All of these variables are functions of time and space. We denote $t \geq 0$ the time variable, and $x \in [0, L]$ the space variable, corresponding to a curvilinear abscissa with x = 0 corresponding to the bottom hole and x = L to the outlet choke position (see Fig. 1). The isothermal equations are as follows,

$$\frac{\partial m}{\partial t} + \frac{\partial m v_L}{\partial x} = 0, \tag{5}$$

$$\frac{\partial n}{\partial t} + \frac{\partial n v_G}{\partial x} = 0, \tag{6}$$

$$\frac{\partial (m v_L + n v_G)}{\partial t} + \frac{\partial (P + m v_L^2 + n v_G^2)}{\partial x} = -(m+n) g \sin \Delta\theta - \frac{2 f (m+n) v_m |v_m|}{D}. \tag{7}$$

In the momentum equation (7), the term $(m + n)g \sin \Delta\theta$ represents the gravitational source term, while $-\frac{-2f(m+n)v_m|v_m|}{D}$ accounts for frictional losses. The mixtures velocity is given as

$$v_m = \alpha_G v_G + \alpha_L v_L. \tag{8}$$

Along with these distributed equations, algebraic relations are needed to describe the system.

2.1 Closure Relations

Both the liquid and gas phase are assumed compressible. This is required for the model to handle the transition from two-phase to single-phase flow. The densities are thus given as functions of the pressure as follows

$$\rho_G = \frac{P}{c_G^2}, \qquad \rho_L = \rho_{L,0} + \frac{P}{c_L^2}, \tag{9}$$

where c_k is the velocity of sound and $\rho_{L,0}$ is the reference density of the liquid phase given at vacuum. Notice that the velocity of sound in the gas phase c_G depends on the temperature as suggested by the ideal gas law. The temperature profile is assumed to be known.

Combining (9) with (4) we obtain the following relations for finding volume fractions from the mass variables:

$$\alpha_G = \frac{1}{2} - \frac{\frac{c_G^2}{c_L^2} n + m + \sqrt{\Delta}}{2\rho_{L,0}}, \tag{10}$$

$$\Delta = \left(\rho_{L,0} - \frac{c_G^2}{c_L^2} n - m\right)^2 + 4 \frac{c_G^2}{c_L^2} n \rho_{L,0} \tag{11}$$

Then the pressure can be found using a modified expression to ensure pressure is define when the gas vanishes

$$P = \begin{cases} \left(\frac{m}{1-\alpha_G} - \rho_{L,0}\right) c_L^2, & \text{if } \alpha_G \leq \alpha_G^* \\ \frac{n}{\alpha_G} c_G^2, & \text{otherwise.} \end{cases} \tag{12}$$

α_G^* is typically chosen as 0.5. Because the momentum equation (7) was written for the gas-liquid mixture, a so-called *slip law* is needed to empirically relate the velocities