STABILIZATION OF GAS LIFTED WELLS BASED ON STATE ESTIMATION

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Abstract: This paper treats stabilization of multiphase flow in a gas lifted oil well. Two different controllers are investigated, PI control using the estimated downhole pressure in the well, and nonlinear model based control of the total mass in the system. Both control structures rely on the use of a state estimator, and are able to stabilize the well flow with or without a downhole pressure measurement available. In both cases stabilization of gas lifted wells increases total production significantly.

Keywords: State estimation with Kalman filter, control, multiphase flow, positive systems.

1. INTRODUCTION

The use of control in multiphase flow systems is an area of increasing interest for the oil and gas industry. Oil wells with highly oscillatory flow are a significant problem in the petroleum industry. Several different instability phenomena related to oil and gas wells exist, in this study unstable gas lifted wells will be the area of investigation.

Gas lift is a technology to produce oil and gas from wells with low reservoir pressure by reducing the hydrostatic pressure in the tubing. Gas is injected into the tubing, as deep as possible, and mixes with the fluid from the reservoir, see Figure 2. The gas reduces the density of the fluid in the tubing, which reduces the downhole pressure, DHP, and thereby increases the production from the reservoir. The lift gas is routed from the surface and into the annulus, the volume between the casing and the tubing. The gas enters the tubing through a valve, an injection orifice.

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The dynamics of highly oscillatory flow in a gas lifted well can be described as follows:

(1) Gas from the casing starts to flow into the tubing. As gas enters the tubing the pressure in the tubing falls. This accelerates the inflow of gas.
(2) The gas pushes the major part of the liquid out of the tubing.
(3) Liquid in the tubing generates a blocking constraint downstream the injection orifice. Hence, the tubing gets filled with liquid and the annulus with gas.
(4) When the pressure upstream the injection orifice is able to overcome the pressure on the downstream side, a new cycle starts.

This type of oscillation is described as casing-heading instability and is shown in the first part of Figure 5 and 6. More information can be found in Xu and Golan (1989).

There are in principle two approaches to eliminate highly oscillating well flow in gas lifted wells: The first approach is to increase the pressure drop caused by friction; either by increasing the gas flow rate, reducing the opening of the production choke or reducing the size of the gas orifice. The second method is the use of active control to stabilize the well flow, which is the subject of this study.

Figure 1 shows a conceptual gas lift production curve. The produced oil and gas rate is a function of the flow rate of gas injected into the well. The curve shows under which conditions the well exhibits stable or highly oscillatory flow. It is important to note that the average production rate may be significantly lower with unstable, see the line "open loop production", compared to stable well flow, see the line "theoretical production". The region of optimum lift gas utilization may lie in the unstable region.

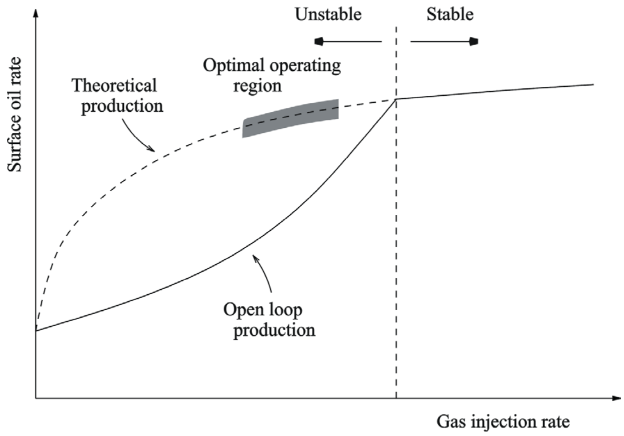

Fig. 1. The gas lift curve with the region of optimum lift gas utilization.

Large oscillations in the flow rate from the well causes lower total production, poor downstream oil/water separation, limits the production capacity and causes flaring. A reduction of the oscillations gives increased processing capacity because of the reduced need for buffer capacity in the process equipment.

Control has to a limited degree been studied for single well systems, see Jansen *et al.* (1999), Kinderen and Dunham (1998) and Dalsmo *et al.* (2002). In addition a two-well simulation study was investigated in Eikrem *et al.* (2002).

The scope of this paper is to study the use of state estimation and control as a tool for stabilizing highly oscillatory well flow in gas lifted wells. Further, earlier work with state feedback for nonlinear positive systems is extended to a realistic output feedback case.

This paper is structured as follows: The system and models are described in Section 2 and 3. A brief theoretical basis is outlined in Section 4 and 5, while the results are shown in Section 6. The paper ends with a discussion and some concluding remarks.

2. SYSTEM DESCRIPTION

2.1 Single Well System

The basis for this study is a realistic gas lifted well, see Figure 2. Reservoir fluid flows through a perforated well, into the wellbore, upwards through the tubing, through the production choke, before it enters downstream equipment which typically will be a manifold and an inlet separator. Gas is injected into the annulus and enters the tubing close to the bottom of the well. The gas mixes with the reservoir fluid to reduce the density of the fluid in the tubing.

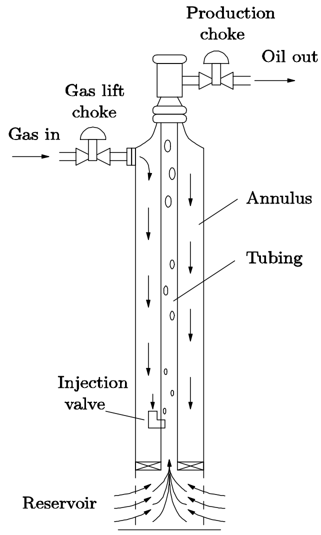

Fig. 2. A gas lifted oil well

The well is described by the following parameters:

- Well parameters
  - · 2048 m vertical well
  - · 5 inch tubing
  - · 2.75 inch production choke
  - · 0.5 inch injection orifice
- Reservoir parameters
  - · $P_R = 160$ bara
  - · $T_R = 108$ ^oC
  - · PI = 2.47E-6 kg/s/Pa
- Separator inlet pressure
  - · 15 bara
- Gas injection into annulus
  - · 0.8 kg/s
  - · 160 bara
  - · 60 ^oC

The productivity index, PI, is defined by

$$PI = \frac{\dot{m}}{\Delta P}$$

where $\dot{m}$ is the total mass flow rate from the reservoir to the well and ΔP is the pressure difference between the reservoir and the bottom of the well. This index relates the mass flow from the reservoir and into the well to the corresponding pressure drop. The PI is assumed constant.

It is assumed that there is no water in the produced fluids, only oil and gas. The gas/oil ratio, GOR, is 80 Sm^3/Sm^3. GOR is defined by:

$$GOR = \frac{\dot{q}_{gas}}{\dot{q}_{oil}}$$

Hence the GOR is defined as the ratio between the volumetric gas rate and the volumetric oil rate at standard temperature and pressure.

The valve model for the production choke includes limitation for the actuator speed, closing time for the valve is 420 sec.

2.2 Simulator

The transient multiphase flow simulator OLGA 2000[2], commonly used in the petroleum industry, is selected as a platform for the simulations. The state estimator and the controllers are implemented in Matlab[3]. OLGA 2000 and Matlab are connected using a Matlab-OLGA link[4].

OLGA 2000 is a modified two-fluid model, i.e. separate continuity equations for the gas, liquid bulk and liquid droplets are applied. Two momentum equations are used, one for the continuous liquid phase and one for the combination of gas and possible liquid droplets. Entrainment of liquid droplets in the gas phase is given by a slip relation. One mixture energy equation is applied. This yields six conservation equations to be solved in each volume (Scandpower, 2001).

The OLGA 2000 model developed for the gas lifted well is built upon the description given in Section 2. The OLGA 2000 model consists of an annulus divided into 25 volumes, and a tubing divided into 25 volumes. The fluid used in the simulations consists of two phases, oil and gas. The inflow of oil and gas from the reservoir is modelled by use of the productivity index, as defined in section 2. The injection rate of lift gas to the annulus is fixed, a fast and well tuned flow controller is assumed used. Fixed boundary conditions for the tubing is assumed, i.e. a fixed reservoir pressure and a fixed separator pressure downstream the production choke.

3. A SIMPLE GAS LIFT MODEL

To be able to develop a state estimator, a simplified model of the gas lifted well is required. This model uses the same boundary conditions as the OLGA 2000 model, but has no mass transfer between the phases, only one volume for the annulus and only one volume for the tubing. The flow between the volumes, into the system and out of the system is controlled by general valve models:

$$w = \begin{cases} C\sqrt{\rho(p_2 - p_1)} & \text{if } \; p_2 \geq p_1 \\ 0 & \text{else} \end{cases} \tag{1}$$

where w is the mass flow, C is the valve parameter, ρ is the density, while the $p_2 - p_1$ is the pressure drop across the restriction. C takes on different values for each restriction.

The pressures in the system are calculated from the mass in the volumes and the pressure drop through the volumes. The pressure at the top of the annulus is calculated by use of the ideal gas law. The pressure at the bottom of the annulus is given by adding the pressure drop from the gas column to the pressure at the top of the annulus. The pressure at the top of the tubing is calculated by the ideal gas law. The volume of the gas in the tubing is given by the volume which is not occupied by oil. The pressure at the bottom of the tubing is given by adding the pressure drop from the fluid column to the pressure at the top of the tubing. Based upon the pressure calculations of the system, the mass flows in and out of the volumes are given by the valve equation (1). The model parameters are tuned based upon OLGA simulations.

To summarize, the following mass balances are assumed to describe the dynamics of the gas lifted well:

$$\begin{aligned} \dot{x}_1 &= w_{iv}(x) - w_{gc}(x) && \text{Mass of gas in annulus} \\ \dot{x}_2 &= w_{gc}(x) - w_{pg}(x,u) && \text{Mass of gas in tubing} \\ \dot{x}_3 &= w_r(x) - w_{po}(x,u) && \text{Mass of oil in tubing} \end{aligned}$$

The symbols are described in Table 1.

Table 1. Symbols

Symbol	**Description**
$w_{iv}(x)$	Gas flow from source into annulus
$w_{gc}(x)$	Gas flow from annulus into tubing
$w_{pg}(x,u)$	Gas flow out of tubing
$w_r(x)$	Oil flow from reservoir into tubing
$w_{po}(x,u)$	Oil flow out of tubing
u	Production choke
M	Total mass in system
λ	Mass control parameter
w_{ref}	Setpoint for flow controller

The simplified model herein is a modified version of the simplified gas lift well model given in Imsland (2002).

[2] Scandpower AS, Norway
[3] The Mathworks Inc
[4] ABB AS, Norway

4. THEORETICAL BASIS

4.1 State Estimation

A standard extended Kalman filter based on the simplified model is developed. Numerical derivation of the simplified model is used to derive a linear model at each time step, corresponding to the current operating point. The covariance matrices for the process and measurement noise are diagonal matrices. The measurement noise matrix is designed based upon the uncertainty of the measurement devices. This matrix is scaled to account for differences in the range of the measurements. The process noise matrix is tuned to obtain a reasonable bandwidth for the state estimator.

4.2 Positive Systems and Feedback Control

Positive systems are dynamical systems which are described by ODEs where the state variables are non-negative. Since mass is an inherently positive quantity, systems modelled by mass balances are a natural example of positive systems, see e.g. Bastin (1999). In Imsland (2002) and Imsland *et al.* (2003) a state feedback controller that exploits positivity is developed. Further, it is shown that the controller exhibits robust stability properties. This work is extended by applying this method in a realistic output feedback setting.

The purpose of the controller is to stabilize the total mass in the system. This is achieved by linearizing the total mass dynamics and exploiting the positivity of the system. The controller calculates the setpoint for an "inner" PI mass flow control loop, and this setpoint is given by:

$$w_{ref} = \max\{0, w_r(x) + w_{iv}(x) + \lambda[M^* - M(x)]\} \tag{2}$$

where M^* is the total mass setpoint. The symbols are described in Table 1.

5. CONTROL STRUCTURES

Several control structures for stabilization of gas lifted wells are available. The possibilities of stabilizing a gas lifted well by use of the measured downhole pressure or the measured casing head pressure have been shown in e.g. Eikrem *et al.* (2002).

5.1 Kalman Filter and Measurements

The Kalman filter uses the available process measurements for correction of the states in the simplified model, in this case the masses in the system. The selected measurements are the pressure at the top of the tubing, the pressure at the top of the casing and the pressure at the bottom of the well. These are realistic measurements from an industrial point of view. Since the downhole pressure measurement is located in a harsh and quite inaccessible location, the effect of failure of this measurement will be investigated.

The Kalman filter includes a check on positivity of the state variables in the sense that state estimates always will be positive.

5.2 Pressure Control and DHP Measurement Failure

The first control structure uses the opening of the production choke as the manipulated variable and the estimated downhole pressure as the controlled variable. The PI-controller is tuned on the basis of process knowledge and iterative simulations. The controller, including the state estimator, is shown in Figure 3.

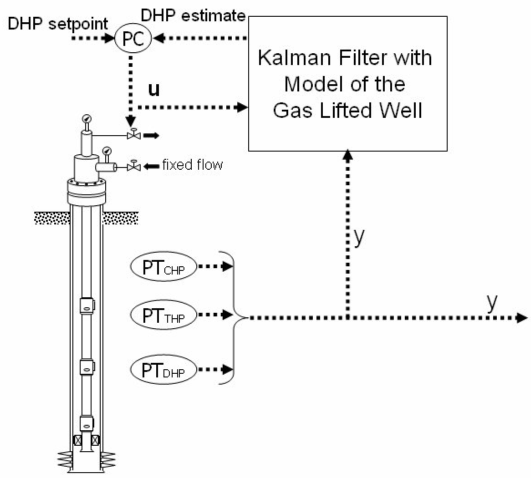

Fig. 3. Control structure for stabilization of a gas lifted well, by controlling the estimated downhole pressure.

5.3 Mass Control and DHP Measurement Failure

The second control structure uses the opening of the production choke as the manipulated variable and the total mass in the system as the controlled variable. In a cascade-manner, the setpoint for the "inner" flow control loop is given by w_{ref}, see (2). The controller including the state estimator is shown in Figure 4.

5.4 Simulation Scenario

The simulations follow the same scenario:

- Timeslot 1, (0-4 h): The well simulator is run in open loop with 50% choke opening.

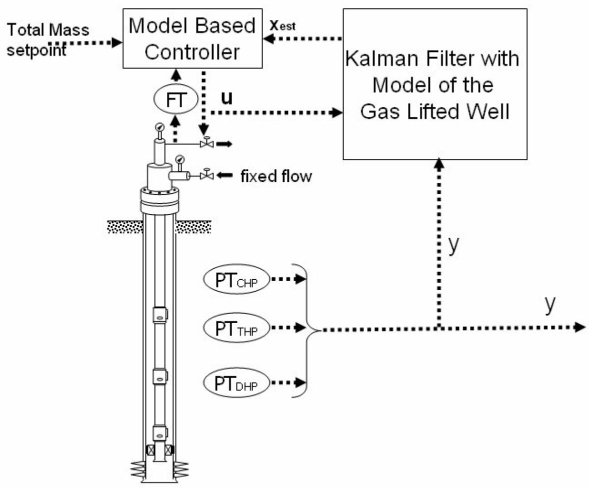

Fig. 4. Control structure for stabilization of gas lifted well, by controlling the total mass in the system.

- Timeslot 2, (4-10 h): The well is stabilized by use of a small choke opening, 20%.
- Timeslot 3: (10-19h): Control using estimated variable, with DHP measurement available.
- Timeslot 4: (19-25h): Control using estimated variable, without DHP measurement available.
- Timeslot 5 (25-30 h): Open loop simulation.

6. SIMULATION RESULTS

6.1 Pressure Control and DHP Measurement Failure

The result from the stabilization of the gas lifted well based upon estimated downhole pressure is given in Figure 5.

The highly oscillatory behaviour is clearly observed during Timeslot 1. The flow is stabilized by closing the valve to 20%, i.e. by increasing the pressure drop caused by friction. The flow is well behaved during Timeslot 3. There is a major disturbance due to the loss of the DHP measurement at 19 hours. This is reasonable since the DHP estimate is heavily influenced by the DHP measurement. The important issue, however, is the fact that the flow is stable. Moreover, the flow becomes highly oscillatory after the controller has been deactivated during Timeslot 5. It should be mentioned that the controller showed a close-to-identical behaviour during Timeslot 3, when the DHP estimate was replaced by the DHP measurement.

The values for the controller parameters for the PI controller are K_p = -0.1 and T_i = 7200 sec. The pressure measurement is given in bara.

The production of oil and gas is given in Figure 6. The stabilization of the gas lifted oil well gives a significant increase in the produced amount of oil and gas. This is particularly pronounced by comparing the production during Timeslot 4 and 5, and this agrees with Figure 1. In the unstable region, the average production rate is 6 kg/s, while the stabilized region gives a production of 15 kg/s.

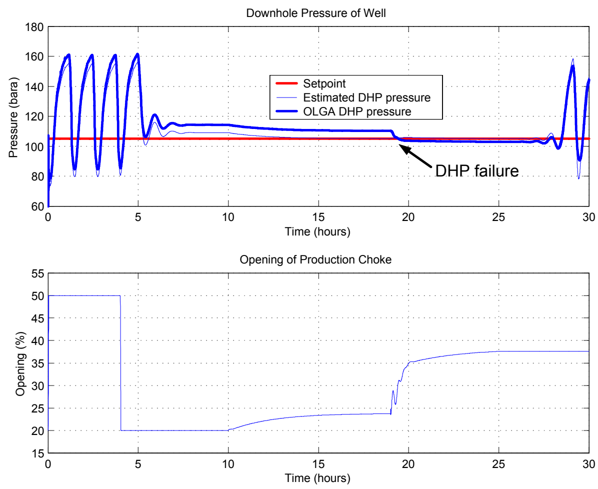

Fig. 5. The estimated and the OLGA downhole pressure for the well. The OLGA well is stabilized by stabilizing the estimated downhole pressure.

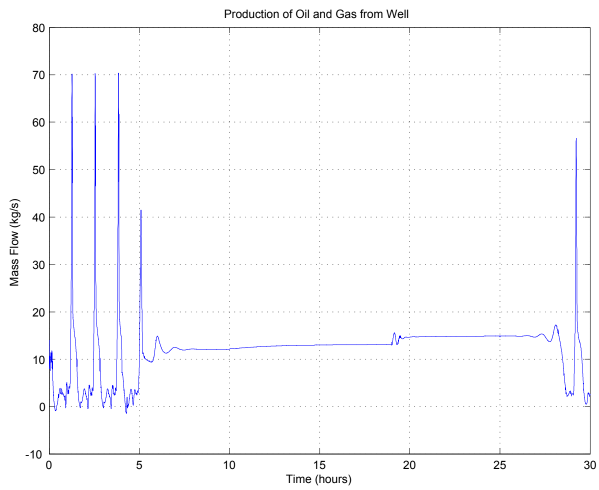

Fig. 6. The oil production from the well when the well is unstable and when it is stabilized.

6.2 Mass Control and DHP Measurement Failure

The result from the stabilization of the gas lifted well based upon mass estimation is given in Figure 7. The downhole pressure measurement fails after 19 hours. The description of the simulation results is identical to the description in the previous case, see Section 6.1. Note again the disturbance when the DHP measurement fails.

Figure 7 reveals that the controller quickly takes the system mass to the desired value, or close to, due to model and estimation error. It can be observed that the input continues to move afterwards. This can be explained by the fact that the point on the "constant mass"-manifold which the system initially converges to, is not the closed loop equilibrium. The slow dynamics on the manifold takes the system to this equilibrium.

The controller parameters for the "inner" mass flow control loop are $K_p = 0.004$ and $T_i = 5$ sec, while the parameter for the "outer" total mass control loop is $\lambda = 0.003$. The mass is given in kg.

The production of oil and gas for the system in open and closed loop is similar to the results given in Figure 6.

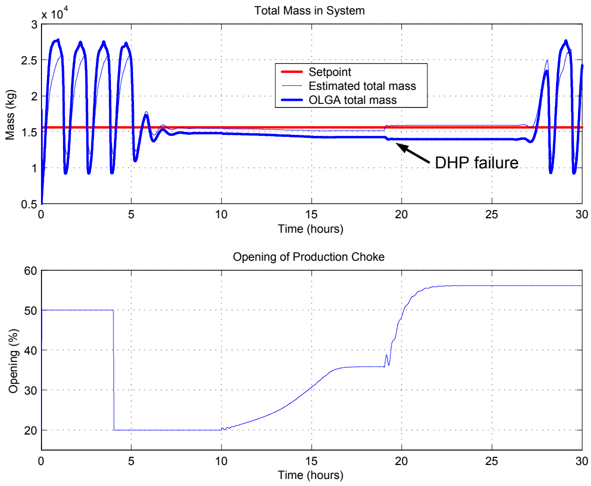

Fig. 7. The estimated and the OLGA total mass for the well. The system is stabilized by controlling the estimated total mass.

7. DISCUSSION AND CONCLUDING REMARKS

This study shows how a low order model in a Kalman filter can provide useful information for control purposes. In particular it is shown how a state estimator can alleviate the common situation in which a difficult accessible downhole measurement fails. It is further shown that stabilization of gas lifted wells is important since it gives an increased production, in this case the production of oil and gas is more than doubled, see Figure 6.

The state estimator functions well both with the traditional PI-controller and the nonlinear controller for positive systems. In this paper the controllers are not pushed to the limit to assess the potential of the nonlinear controller. The possible merit of the nonlinear controller has been showed in a realistic output feedback application.

The simplified model needs to be well tuned to reflect the dynamics of the real system as the DHP measurement fails. The main challenge is related to the estimation of downhole conditions upon the loss of the DHP measurement. In practice the tuning is done by adjusting the valve parameters, see (1). Typically they have been changed $\pm 25\%$ compared to their original values. It should be mentioned that the low order model is observable at all times.

An alternative to the current approach is the use of an augmented Kalman filter in which model parameters are tuned online.

To re-iterate there are alternative control structures, that do not involve downhole measurements nor estimation, that are able to stabilize the highly oscillatory flow for this particular well. There is still considerable value in the problem addressed in this paper since other more complex well completions may require measurements or estimates of downhole conditions.

8. ACKNOWLEDGEMENT

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REFERENCES

Bastin, G. (1999). Issues in modelling and control of mass balance systems. In: *Stability and stabilization of Nonlinear Systems* (Dirk Aeyels, Françoise Lamnabi-Lagarrigue and Arjan van der Schaft, Eds.). Springer.

Dalsmo, M., E. Halvorsen and O. Slupphaug (2002). Active feedback control of unstable wells at the Brage field. Society of Petroleum Engineers. San Antonio, Texas, USA. SPE paper no. 77650.

Eikrem, G. O., L. S. Imsland, B. A. Foss, B. Hu and M. Golan (2002). Stabilization of gas lifted wells. In: *IFAC 2002 World Congress, Barcelona.*

Imsland, L. S. (2002). Topics in Nonlinear Control - Output Feedback Stabilization and Control of Positive Systems. PhD thesis. Norwegian University of Science and Technology, Department of Engineering Cybernetics.

Imsland, Lars, Bjarne A. Foss and Gisle O. Eikrem (2003). A state feedback controller for a class of positive systems: Application to gas lift stabilization. In: *Proc. 5th European Control Conference ECC'03*. Cambridge, UK.

Jansen, B., M. Dalsmo, L. Nøkleberg, K. Havre, V. Kristiansen and P. Lemetayer (1999). Automatic Control of Unstable Gas Lifted Wells. Houston, Texas. SPE paper no. 56832.

Kinderen, W.J.G.J. and C.L. Dunham (1998). Real-Time Artificial Lift Optimization. Abu Dhabi. SPE paper no. 49463.

Scandpower (2001). OLGA 2000. http://www.scandpower.no.

Xu, Z. G. and M. Golan (1989). Criteria for operation stability of gas lift. SPE paper no. 19362.