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Stabilization of gas-lift oil wells using topside measurements

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Abstract: Highly oscillatory flow regimes that can occur in gas-lift oil wells have been successfully treated using conventional linear control. However, these control systems rely on downhole pressure measurements which are unreliable or even unavailable in some cases. In this paper we propose a solution based on a high gain observer for the state of the process. The estimates are used to compute the downhole pressure, that is the controlled variable considered in the feedback control. Moreover, we propose an estimator to extend a nonlinear observer already presented in the literature, and then we compare the performances. The key feature of the solution proposed is its simplicity and that it relies only on measurements easily obtainable from the top of the single well, and thus it is immediately applicable to multiple-well systems where, since there is often one common outflow manifold, it would be hard to see from the outflow measurements which well is operating in an oscillatory regime.

1. INTRODUCTION

Oil wells with highly oscillatory flow constitute a significant problem in the petroleum industry. This is the case, for instance, for oil wells on mature fields, where artificial lift techniques are used to increase tail-end production. Gas lift is one of the most widely used technologies to maintain, or to increase, the production from wells characterized by low reservoir pressure.
With gas lift, gas is injected into the tubing, as close as possible to the bottom of the well, and mixed with the fluid from the reservoir (Fig. 1). The gas reduces the density of the fluid in the tubing, which reduces the downhole pressure, and thereby increases the production from the reservoir. The lift gas is routed from the surface into the annulus, the volume between the casing and the tubing, and enters the tubing through a unidirectional valve that does not permit backflows.
A negative aspect of this technique is that gas lift can induce severe production flow oscillations. The oscillations caused by the dynamic interaction between injection gas in the casing and multiphase fluid (oil/gas mixture) in the tubing are a phenomenon known as *casing-heading instability*. This instability can be explained as follows. Consider a situation where there is no (or low) flow in the tubing. The bottom well pressure is high due to the weight of the fluid column in the tubing. Gas is then inserted in the annulus, but because of the high bottom hole pressure, initially it does not enter the tubing, the injection valve stays closed. The gas starts to compress in the annulus, and after some time it gets enough pressure to open the injection valve and to start to enter in the tubing. As gas enters the tubing the density of the fluid, and consequently the downhole pressure, decreases, accelerating the inflow of lift gas and increasing the production of oil. As gas continues to enter the tubing, the pressure in the annulus falls until the liquid in the tubing causes the injection valve to close, hence the tubing starts to fill with liquid and the annulus to fill with gas. Since no gas is injected into the tubing the production decreases again to the natural production of the well, which might be zero. A new cycle starts when the pressure in the annulus becomes high enough to penetrate the valve.
The fluctuating flow typically has an oscillation period of a few hours and is distinctively different from short-term oscillation caused by hydrodynamic slugging.
The casing-heading instability introduces two production-related challenges: average production is lower compared to a stable flow regime, and the highly oscillatory flow puts strain on downstream equipment. Fig. 2 shows a conceptual gas-lift production curve. The produced oil rate is a function of the flow rate of the gas injected into the well. Maximizing the performance of a gas-lifted well can be summarized as maximizing the oil production by keeping gas injected in the tubing at a certain level (decided by topside production limitations) that may be in the unstable region. In maximizing the oil production it is desired to keep the flow stable, to mantain a high processing ability topside and to have higher production capacities, as can be seen in Fig. 2.
Efforts have been exerted both in academia and industry to find optimal solutions based on control theory (Eikrem et al. [2002], Eikrem et al. [2004], Aamo et al. [2004], Eikrem et al. [2006], Havre and Dalsmo [2002], Skofteland and Godhavn [2003]).
An extended Kalman filter (Eikrem et al. [2004]) and a nonlinear observer (Aamo et al. [2004]) have been used to estimate the state of the system, and then to use them to

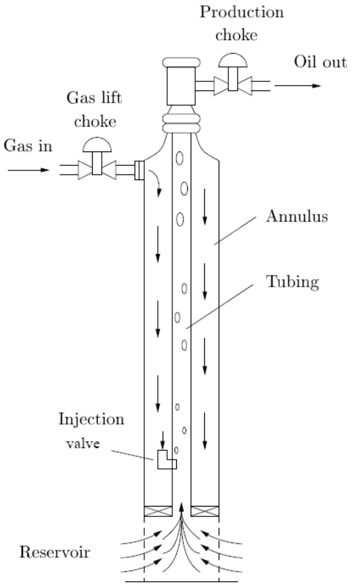

Fig. 1. A gas lifted oil well scheme.

compute the downhole pressure needed to close the control loop that stabilizes the system.

In this paper we propose a simpler solution based on a high gain observer (HGO). The measurements used are only the pressure of gas in the annulus, the pressure of the fluid at the top of the tubing and the density at the top of the tubing. The measurement of the flow through the production choke is not required, so this solution can be easily applied to multiple-well systems, where usually there is a common manifold where all the wells are connected. In these systems in case of slugging, the measurement of the total flow would not be informative about which well in the system is operating in the unstable regime.

The nonlinear observer (NLO) designed in Aamo et al. [2004] was shown to be exponentially fast, but has the assumption that one of the states is measured. We remove this assumption using an estimator extracted from the structure of the HGO. We provide also a stability analysis of the estimator. Then, the performances of the HGO is compared with the one of the combination estimator-NLO.

The paper is organized as follows: in Section 2 we present the mathematical model of the process; in Section 3 we design the observer, the estimator, and show open-loop simulation graphs; in Section 4 is presented an output feedback stabilization scheme combining the observer with a proportional integral (PI) control of the estimated down-hole pressure, and; Section 5 presents final remarks.

2. MATHEMATICAL MODEL

Commonly in the petroleum industry, the process described in Section 1 is simulated by the transient multi-phase simulator OLGA 2000 (Scandpower AS), that constitutes the state-of-the-art available nowadays.

The OLGA 2000 model developed for the gas lift well is highly accurate taking into account many aspects of the real system, and therefore is complicated and not suitable for control design purposes. Here we use a simplified model due to Eikrem et al. [2002].

The process is modelled by three states: x_1 the mass of gas in the annulus; x_2 the mass of gas in the tubing; x_3 the mass of oil in the tubing. Looking at Fig. 1, we have from mass balances

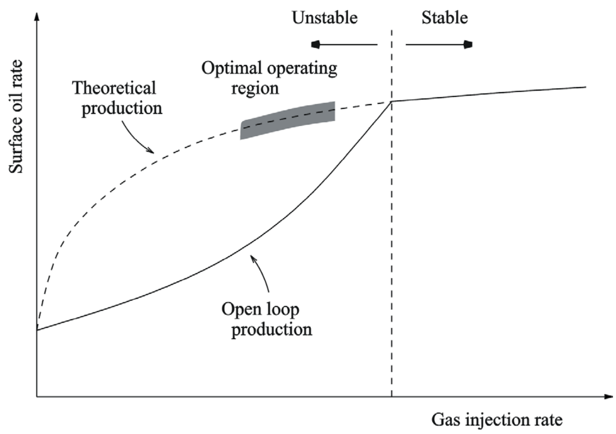

Fig. 2. Oil production as function of gas injection rate. The dotted line is the production calculated by steady state simulations assuming stable operation. The solid line is generated by dynamic simulations.

$$\dot{x}_1 = w_{gc} - w_{iv}, \tag{1}$$
$$\dot{x}_2 = w_{iv} - w_{pg}, \tag{2}$$
$$\dot{x}_3 = w_{ro} - w_{po}, \tag{3}$$

where w_{gc} is the mass flow rate of lift gas into the annulus, considered constant; w_{iv} is the mass flow rate of lift gas from the annulus into the tubing; w_{pg} is the mass flow rate of gas through the production choke; w_{ro} is the oil mass flow rate from the reservoir into the tubing; and w_{po} is the mass flow rate of produced oil through the production choke.

The flows are modelled by

$$w_{gc} = constant, \tag{4}$$
$$w_{iv} = C_{iv}\sqrt{\rho_{ai}\max\{0, p_{ai} - p_{wi}\}}, \tag{5}$$
$$w_{pc} = C_{pc}\sqrt{\rho_m \max\{0, p_{wh} - p_s\}}u, \tag{6}$$
$$w_{pg} = \frac{x_2}{x_2 + x_3} w_{pc}, \tag{7}$$
$$w_{po} = \frac{x_3}{x_2 + x_3} w_{pc}, \tag{8}$$
$$w_{ro} = C_r\left(p_r - p_{wb}\right). \tag{9}$$

C_{iv}, C_{pc} and C_r are constants, u is the production choke opening ($u(t) \in [0, 1]$), ρ_{ai} is the density of gas in the annulus at the injection point, ρ_m is the density of the oil-gas mixture at the top of the tubing, p_{ai} is the pressure in the annulus at the injection point, p_{wi} is the pressure in the tubing at the gas injection point, p_{wh} is the pressure at the well head, p_s is the pressure in the separator, p_r is the pressure in the reservoir, and p_{wb} is the pressure at the well bore.

The separator pressure, p_s, is assumed to be held constant by a control system. The reservoir pressure, p_r, is assumed to be slowly varying and therefore is treated as constant. Note that the flow rates through the production valve and the injection valve are restricted to be positive.

The densities are modelled as follows

$$\rho_{ai} = \frac{M}{RT_a} p_{ai}, \tag{10}$$

$$\rho_m = \frac{x_2 + x_3}{L_w A_w}, \quad (11)$$

and the pressures as follows

$$p_{ai} = \left(\frac{RT_a}{V_a M} + \frac{gL_a}{V_a} \right) x_1, \quad (12)$$

$$p_{wh} = \frac{RT_w}{M} \frac{x_2}{L_w A_w - v_o x_3}, \quad (13)$$

$$p_{wi} = p_{wh} + \frac{g}{A_w} (x_2 + x_3), \quad (14)$$

$$p_{wb} = p_{wi} + \rho_o g L_r. \quad (15)$$

M is the molar weight of the gas, R is the gas constant, T_a is the temperature in the annulus, T_w is the temperature in the tubing, V_a is the volume of the annulus; L_a is the length of the annulus; L_w is the length of the tubing, A_w is the cross-sectional area of the tubing above the injection point, L_r is the length from the reservoir to the gas injection point, A_r is the cross-sectional area of the tubing below the injection point, g is the gravity constant, ρ_o is the density of the oil, and v_o is the specific volume of the oil. The oil is considered incompressible, so $\rho_o = 1/v_o$. The molar weight of the gas, M, is assumed constant, and the temperatures, T_a and T_w, are assumed slowly varying and therefore treated as constants.

The dynamics of the simplified model has been compared to those given by the OLGA 2000 multiphase simulator in Imsland [2002] and found to be in satisfactory agreement. It should be noted, however, that the aim of the simplified model is just to capture the casing-heading instability, and that a number of other instabilities that may occur in gas-lift oil wells are not captured as well, as for instance tubing-heading instability, tubing-reservoir interactions, hydrodynamic slugging.

3. STATE ESTIMATION

In practice, the measurements downhole in the tubing are to be considered quite unreliable because of the harsh conditions in which the sensors have to operate. Considering also that the maintenance of those sensors is basically impossible, sometimes downhole measurements are even not available at all.
In this paper we assume that only well-top measurements are available, and in particular the pressure in the annulus, that gives $y_1(t) = p_{ai}(t)$, the pressure at the top of the tubing, $y_2(t) = p_{wh}(t)$, and the density at the top of the tubing, $y_3(t) = \rho_m(t)$.

3.1 Observer

The HGO used has a particularly simple structure since it is only a copy of the simplified model, together with the correction terms. The observer uses the available process measurements for the correction of the state estimates in the simplified model.
From (12) we obtain

$$x_1 = \left(\frac{RT_a}{V_a M} + \frac{gL_a}{V_a} \right)^{-1} y_1, \quad (16)$$

from (13)

$$x_2 = \frac{M (L_w A_w - v_o \hat{x}_3)}{RT_w} y_2 \quad (17)$$

and from (11)

$$x_3 = L_w A_w y_3 - \hat{x}_2 \quad (18)$$

needed for the correction terms.
The observer equations are then

$$\dot{\hat{x}}_1 = w_{gc} - \hat{w}_{iv} + K_1 (x_1 - \hat{x}_1) \quad (19)$$

$$\dot{\hat{x}}_2 = \hat{w}_{iw} - \hat{w}_{pg} + K_2 (x_2 - \hat{x}_2) \quad (20)$$

$$\dot{\hat{x}}_3 = \hat{w}_{ro} - \hat{w}_{po} + K_3 (x_3 - \hat{x}_3) \quad (21)$$

where K_1, K_2 and K_3 are positive constant gains, and $\hat{w}_{iv}$, $\hat{w}_{pg}$, $\hat{w}_{ro}$ and $\hat{w}_{po}$ have the same structure of (5)-(15) where instead of the states x_1, x_2 and x_3 we have the estimates $\hat{x}_1$, $\hat{x}_2$ and $\hat{x}_3$ respectively. Since (13) and (11) contain both x_2 and x_3, in (17) and (18) we use the estimates $\hat{x}_3$ and $\hat{x}_2$ instead.
At the time of writing this paper, the stability of the observer proposed is supported only by simulation results. Even if the simulations show that the observer is exponentially converging to the real states, the non smoothness of the state equations (due to the max functions and the square root terms) does not allow an immediate proof of stability. In works such as Hammouri et al. [2002], Gautier et al. [1992] the stability of high gain observers for a class of nonlinear systems has been analyzed and conditions have been given. Such results are promising, and efforts are in train to extend them to classes of nonlinear systems like the gas-lifted oil well.

3.2 Estimator for the mass of gas in the annulus

The NLO designed and analyzed in Aamo et al. [2004] estimates the state x_2 and x_3 under the assumption that the state x_1 is measured. It was shown that the NLO is exponentially fast. In this paper we use the equation (19) of the HGO to extend the NLO providing an estimator for the state x_1 based on a well-top measurement.
Considering (1) and (19), the error, $\tilde{x}_1 = x_1 - \hat{x}_1$, is governed by

$$\dot{\tilde{x}}_1 = -w_{iv} + \hat{w}_{iv} - K_1 \tilde{x}_1 \quad (22)$$

Since the mass is an inherently positive quantity and that the system is modeled by mass balances, we have

$$w_{iv}(x) \geq 0 \quad \forall x \geq 0, \quad (23)$$

$$\hat{w}_{iv} \leq C_{iv} \sqrt{\frac{M}{RT_a}} \left(\frac{RT_a}{V_a M} + \frac{gL_a}{V_a} \right) \hat{x}_1 \quad \forall \hat{x} \geq 0. \quad (24)$$

Taking the Lyapunov function candidate $V = \frac{1}{2}\tilde{x}_1^2$ we have

$$\dot{V} = \tilde{x}_1 \dot{\tilde{x}}_1 \quad (25)$$

and using (23), (24) and $\tilde{x}_1 = x_1 - \hat{x}_1$

$$\dot{V} \leq C x_1 \tilde{x}_1 - (C + K_1) \tilde{x}_1^2 \quad (26)$$

where $C = C_{iv} \sqrt{\frac{M}{RT_a}} \left(\frac{RT_a}{V_a M} + \frac{gL_a}{V_a} \right)$ is a positive constant. Since x_1 is bounded, we can write $x_1 \leq \delta_1$, where δ_1 is

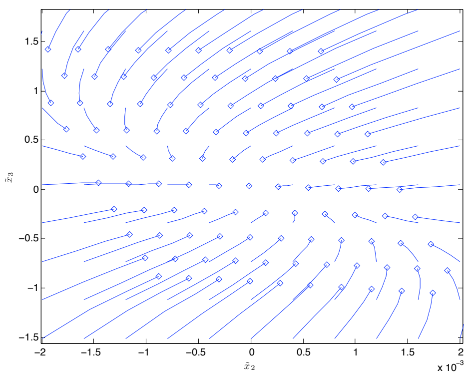

Fig. 3. Phase portrait ($u = 0.4$).

a constant. Using input-to-state stability (Khalil [2000] paragraph 4.9) we have

$$\dot{V} \leq 0 \quad \forall \tilde{x}_1 \geq \frac{C\delta_1}{(C + K_1)\,\theta} = \rho(\delta_1). \qquad (27)$$

where $0 < \theta < 1$ and the function $\rho(\delta_1)$ belongs to class κ. This shows that (22) is ISS with respect to x_1, that means it is always possible to make the observer to converge exponentially fast toward the real state and to keep the error as small as desired changing the value of the gain K_1. This is a coarse result due to the assumption (23) and (24) that allowed to make (22) independent from $x_2, \hat{x}_2, x_3, \hat{x}_3$. Actually the simulations show that the error exponentially converges to 0. Anyway it gives a stability proof of the estimator for x_1, and using this in connection with the NLO forms an exponentially fast observer using only well-top measurements.

Moreover, it is possible to see the HGO as a cascade interconnection of two systems: the estimator for x_1 and the sub-observer composed by (20)-(21). The error dynamics of the sub-observer are governed by the second order system $\dot{\tilde{x}}_2 = \dot{x}_2 - \dot{\hat{x}}_2$, $\dot{\tilde{x}}_3 = \dot{x}_3 - \dot{\hat{x}}_3$. This can be considered autonomous if we fix the input u and consider x_1 given by the estimator ($x_1 = \hat{x}_1$). The qualitative behavior of such system can be easily visualized by a phase portrait in the phase plane. Considering several inputs u ($u(t) \in [0, 1]$), it has been seen that the origin is a locally asymptotically stable equilibrium point (Fig. 3 shows the case $u = 0.4$).

3.3 Open-loop simulations

The numerical coefficients used for the simulations are taken from Eikrem et al. [2006] and refer to a laboratory installation where compressed air is used as the lift gas and water as the produced fluid. The production tube measures $18m$ in height and has an inner diameter of $20mm$.

In the simulations in this paper, gas is fed into the annulus at a constant rate of $w_{gc} = 0.1 \times 10^{-3} kg/s$. All the simulations are implemented in Matlab. The initial values equal steady state conditions. Values for the HGO correction gains that make the estimates converge in $3sec$ were easily found after a few tries: $K_1 = 1$, $K_2 = 1$ and $K_3 = 1$.

Fig. 4 shows that the states estimated by the HGO converge exponentially fast to the real states. Fig. 5 shows the downhole pressure calculated from the states estimates compared to the value obtained from the simulated system.

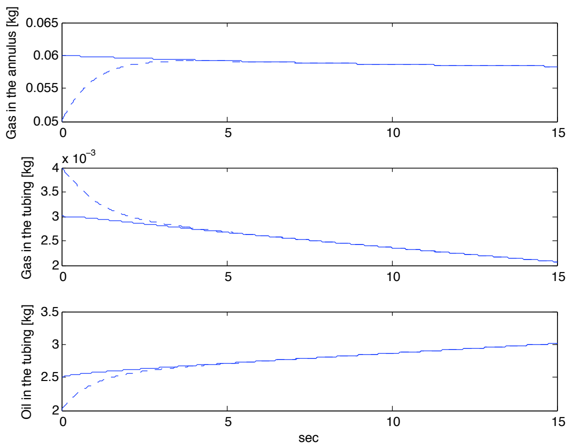

Fig. 4. States of the system. The full line are the states simulated, the dashed line are the states estimated.

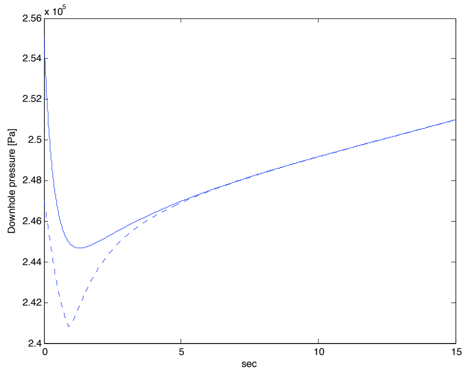

Fig. 5. Downhole pressure. The full line is the pressure simulated, the dashed line is the pressure estimated.

From Fig. 6 it is possible to see how raising the opening of the production choke from $u = 0.2$ to $u = 0.8$ (switching at $t = 200sec$) causes severe slugging in the production.

The HGO was compared with the NLO proposed in Aamo et al. [2004] in combination with the estimator proposed in Subsection *3.2*. The NLO is an exponentially fast nonlinear observer, but it is characterized by a structure more complicated than the one of the HGO. In Fig. 7 the two observers are compared, and it can be seen that the convergence is extremely quick for both (notice the time scale). The tuning of the HGO gains to obtain this result was quite straightforward ($K_1 = 20$, $K_2 = 15$ and $K_3 = 15$), thanks to its simple structure. The same cannot be said for the NLO, that required quite some time to well tune its gains.

4. FEEDBACK STABILIZING CONTROL

It can be seen from simulations that a higher rate of injection gas will stabilize the well, but not at an optimal operating point. A fixed choke opening will also stabilize the well, provided the opening of the choke is reduced until the flow from the well is stable. The reason why an increased amount of lift gas and/or a reduced choke opening gives stable flow is that the flow in the tubing changes from gravitation dominant to friction dominant flow. An improved production solution is to stabilize the well system in the unstable region with feedback control.

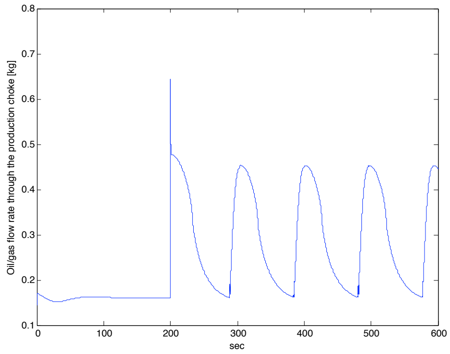

Fig. 6. Mixture oil/gas flow rate through the production choke.

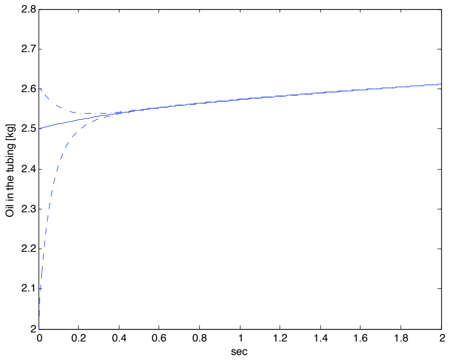

Fig. 7. Mass of oil in the tubing. The solid line is the state simulated, the dashed line is the state estimate with the HGO proposed, the dashdoted line is the state estimated with the NLO.

4.1 Controller

In Eikrem et al. [2006] it has been shown that casing-heading instability can be eliminated by stabilizing the downhole pressure using a PI control:

$$u = K_p \left(p_{wb} - p_{wb}^*\right) + K_i \int \left(p_{wb} - p_{wb}^*\right) dt \qquad (28)$$

where p_{wb} is the downhole pressure and p_{wb}^* is its desired set point, chosen usually by the operator. The means of actuation is the production choke ($u(t) \in [0, 1]$). However the downhole pressure is not an easy measurement to obtain, due to the harsh condition in which the pressure sensor has to operate. In addition, high failure rate of these sensors is reported by oil companies, and their maintenance causes costs and problems with the production of oil.

In this paper we propose an alternative to the downhole pressure measurement, and that is to replace p_{wb} with its estimate $\hat{p}_{wb}$.

The pressure $\hat{p}_{wb}$ can be obtained from (15) by using the states estimated with the observer described in the previous Section. The control structure is shown in Fig. 8.

4.2 Closed-loop simulations

The set point is chosen as $p_{wb}^* = 2.64Pa$. The controller was tuned using a combination of process knowledge and iterative simulations, and found $K_p = -0.3 \cdot 10^{-5}$ and $K_i = -0.006 \cdot 10^{-5}$.

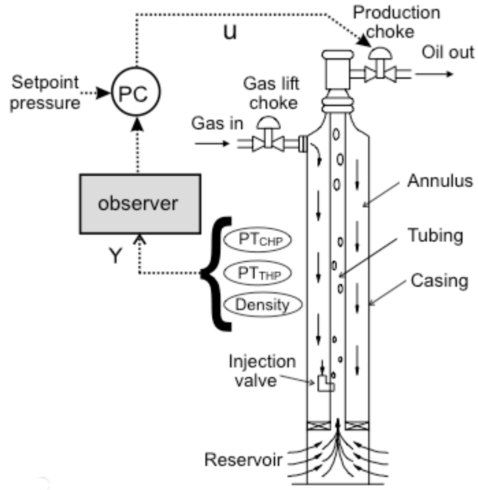

Fig. 8. Control structure for stabilization of a gas-lift well, by controlling the estimated downhole pressure.

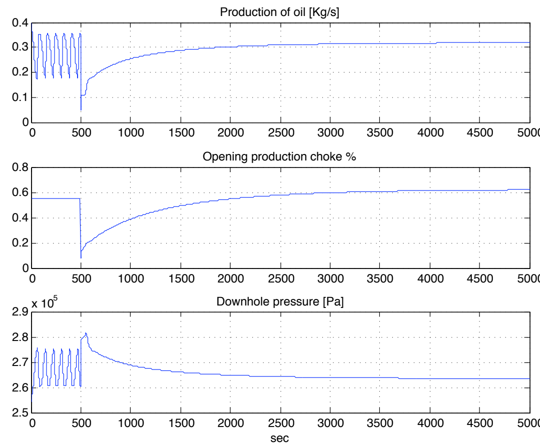

Fig. 9. Production of oil. Opening of the production choke. Downhole pressure.

Fig. 9 represents the following simulated scenario: at the beginning the gas-lift oil well is simulated in open loop with a 55% choke opening. The initial values equal steady state conditions. At time $t = 500sec$ the controller is connected to the system. After the control loop has been closed, the oscillations are quickly stabilized, even if it takes about $50min$ ($3000sec$) before the system is brought to the desired setpoint. This is roughly the time taken to build up the pressure in the annulus.

It can be seen also how the controller gently opens the production choke from 55% to 62%, this stabilizes the production of oil eliminating the casing-heading instability. Note that also the production is increased.

The downhole pressure is stabilized to $2.64Pa$.

The case of noisy measurements was also considered. Since the density is the measurement that can be more subject to uncertainty, we assume to have y_3 corrupted by white noise (zero mean, variance $100kg/m^3$ corresponding to 10% of the nominal value, Fig. 10). In Fig. 11 it can be noted that the controller successfully operates on the production choke valve so as to eliminate the oscillations in the oil production.

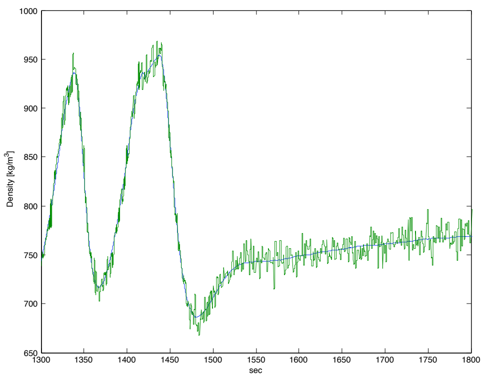

Fig. 10. Density measurement plus the uncertainty on the measurement.

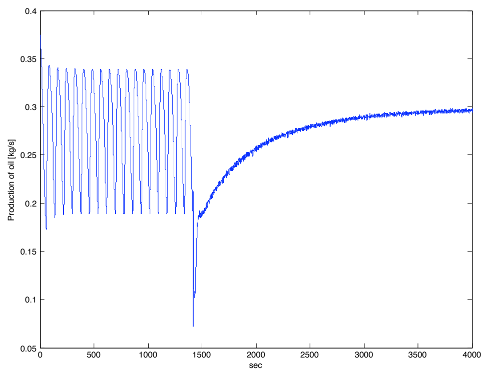

Fig. 11. Stabilization of the oil production using the downhole pressure obtained with noisy measurements.

In industry, gain scheduling is often used to adapt the gains of the PI controller as the operating point of the production valve changes. This increases the performance, but in some cases gain scheduling may also be necessary to keep the system stable since the gain values computed for a certain steady state choke opening might not have sufficient control authority to stabilize the casing-heading instability for higher steady state choke openings, as was shown in Eikrem et al. [2006]. Gain scheduling can be used also with the control structure proposed in this paper to have a better stabilizing controller in the all ranges of production choke opening, implementing hysteresis to prevent frequent change due to noise in the pressure estimate.

5. CONCLUSION

In this paper the problem of casing-heading instability that can occur in gas-lifted oil wells was considered. Casing-heading instability causes highly oscillatory oil flow rate, leading to lower production and lower processing capacity. The solution proposed was the use of a closed-loop control. The control structure presented uses the opening of the production choke as the manipulated variable and the downhole pressure as controlled variable.

Since measurements downhole in the tubing are quite unreliable, we proposed a high gain observer to estimate the states using only well-top measurements, and then using these estimates to reconstruct the downhole pressure needed. Moreover, using part of the HGO we designed an estimator for the mass of gas in the annulus and used it to extend the exponentially fast NLO proposed in Aamo et al. [2004].

The performance of the HGO was demonstrated in simulations and compared with the combination $x_1$estimator-NLO. It was seen that for basically the same performance, the HGO presents a simpler tuning capability.

The control structure proposed can also be used in a straightforward fashion as a backup strategy: it is possible to switch from a control structure based on the measured downhole pressure to the structure based on well-top measurements in case of sensor failure.

Even if the simulations showed that the observer converges exponentially fast, the stability is not yet theoretically supported. The significant nonlinearity of the model equations makes the problem nontrivial. The stability of high gain observers for a class of nonlinear systems has been analyzed in the literature, and conditions have been given. An extension of the analysis to classes of nonlinear systems like the gas-lifted oil well system represents ongoing research.

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