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STABILITY ANALYSIS AND STABILIZATION OF GAS LIFT SYSTEMS

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Abstract. *Under certain operating conditions, the gas lift interacts with the production flow in a way that it causes cyclic variations in pressure and production rate. This work focuses on Casing-Heading suppression, which can reduce production losses and increase operational efficiency. Traditional stability criteria for Gas Lift systems are revisited and an the Alhanati* et al. *(1993) stability criterion motivates some stabilization strategies that are analyzed such as production choke adjustments, replacement of Gas Lift valves and active control systems.*
A simple non-linear two-phase flow model is considered to capture the essential dynamics of the casing-heading phenomenon with three state variables. A reduction of the model is given through a linear fit such that one of the state variables is linearly dependent and the states trajectory of the oscillation can be analyzed as a limit cycle. Although it is possible to prove that this two dimensional system has a limit cycle, this work presents the vector field in the phase plane representing the directions of the state variables at each point to highlight both the unstable fixed point and the limit cycle. A linearization at a fixed point inside the limit cycle is provided along with a stability map based on the state matrix eigenvalues for different production choke settings to identify where the casing-heading occurs in order to suppress it.
This work aims to guide a petroleum engineer in order to decide among different strategies to suppress casing-heading while minimizing production losses. The average production rate of the oscillating well is obtained from simulation and it is used as base case. Some of the most common strategies are considered separately and are compared in terms of production rate. First, a feedback Linear Quadratic Gaussian control is designed to stabilize the production by operating the production choke measuring the bottom-hole pressure, which increases the production rate compared to the oscillating situation despite increasing the local pressure drop. This occurs because the average friction losses are extremely high during production oscillations. Then the throat area of the gas lift valve is modified to stabilize the production. Also a simplified model of the proportional response gas lift valve is given and also used to suppress the casing-heading. Finally, a control system is proposed based on a surface-controlled electric gas lift valve.

Keywords: *Gas Lift Stability; Casing Heading; Gas Lift Valves; Control Systems*

1. INTRODUCTION

According to Hu (2004) both natural flowing wells and gas lift wells can experience cyclic variations of pressure and flow rates. Casing-heading was first found in unstable natural flowing wells completed without production packer. This work is concerned only with casing-heading in gas lift wells completed with production packers.

The mechanism of casing-heading in a gas lift well is described by Eikrem (2006). First, the gas from the casing starts to flow into the tubing, reducing the tubing pressure which thus increases the production rate. As the gas pushes the major part of liquid out of the tubing, the casing pressure falls and the liquid in the tubing generates a blocking constraint downstream the injection orifice. By the time the annulus gets filled with gas (and the tubing with liquid), the pressure upstream the injection orifice is able to overcome the pressure on the downstream side and a new cycle starts.

Eikrem (2006) also points out that the oscillating flow occurring at large choke openings is highly undesirable because it not only reduces the total production but also introduces significant disturbances to the downstream processing facility, which may cause inefficiencies or even shutdowns due to high peaks of gas flow rates or liquid overflow. Compressors can also be affected and fatigue problems can occur in some equipment. Choking can reduce oscillations at a cost of production losses.

This work analyses several strategies to suppress casing-heading and the main purpose is to qualitatively present the impact of each strategy on the production rate. For practical purposes it is important to have a very reliable simulation model of the well and perform a detailed analysis of each strategy to have enough information in order to make the most profitable decision.

2. NON-LINEAR DYNAMIC MODEL

Conventional modelling of transient flow in wells uses partial differential equations for mass and momentum conservation for each phase. When heat transfer is important, the energy conservation equations are also considered. These models can be applied to a wide range of operational conditions but they are hardly applied to design control systems (Storkaas, 2005).

The model used for control purposes should only include those physical phenomena that are significant to describe the

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dominant behaviour of a system, in this work, the casing-heading. A simple model was developed (Eikrem *et al.*, 2008) based solely on the conservation of mass principle and it has the capability to capture the main dynamics of casing-heading qualitatively.

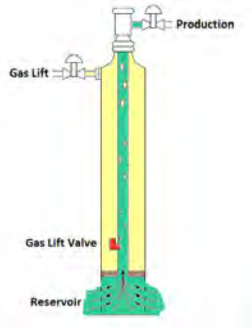

Figure 1. Gas Lift Oil Well (Eikrem *et al.*, 2008) - modified.

Consider a model represented in Fig. 1, which has the tubing filled with liquid inflow from reservoir and gas inflows from the reservoir and from the annulus. The gas flow rate to the annulus is controlled by a surface injection choke that keeps the flow constant. Outflow can be regulated by the production choke.

The state variables are the masses of gas in the annulus (x_1) and in the tubing (x_2) and the mass of liquid in the tubing above the injection point (x_3). Considering two control volumes, the tubing and the annulus, the application of mass conservation, represented in Fig. 1, yields:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} w_{gc} - w_{iv} \\ w_{iv} + w_{rg} - w_{pg} \\ w_{po} - w_{ro} \end{bmatrix} \tag{1}$$

where w_{gc} is a constant mass flow rate of gas into the annulus, w_{iv} is the mass flow rate of gas through the gas lift valve, w_{rg} is the mass flow rate of gas from the reservoir into the tubing, w_{pg} is the mass flow rate of gas through the production choke, w_{ro} is the flow rate of oil from the reservoir into the tubing, and w_{po} is the mass flow rate oil through the production choke. The parameter w_{gc} set constant is a boundary condition to calculate the injection pressure and a constant injection pressure could have been alternatively considered instead. For practical purposes, it depends on the equipment used to control the injected gas.

All non-constant flows are modelled as simplified valve equations, following (Eikrem *et al.*, 2008), except that the Inflow Performance Relationship (IPR), which is a relationship between the producing bottom-hole pressures and its corresponding production rates, is also considered as a simplified valve equation.

The gas lift valve equation is a reasonable approximation to the sub-critical region of the performance curve of an orifice valve. It can be slightly modified to take into account critical flow (truncating at the critical ratio, even if it causes a discontinuity at the slope of the performance curve of the valve, because it is only an approximation) but for this work it is not necessary. However, this equation is modified to simulate the proportional response valve. The "max" function in the equation acts like a check valve and no back flow is admitted.

$$w_{iv} = C_{iv}\sqrt{\rho_{a,i} max\left[0, p_{a,i} - p_{wi}\right]} \tag{2}$$

The flow through the production choke requires a different approach because there are two phases flowing through. A function to represent the production choke setting is also required.

$$w_{iv} = C_{pc}\sqrt{\rho_m max\left[0, p_{wh} - p_{ps}\right]} f_{pc}\left(u\right) \tag{3}$$

$$w_{pg} = \frac{x_2}{x_2 + x_3} w_{pc} \tag{4}$$

$$w_{pg} = \frac{x_3}{x_2 + x_3} w_{pc} \tag{5}$$

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The IPR is widely represented by the Vogel equation, but in this work a valve equation was used to represent the reservoir response.

$$w_{ro} = C_{ro}\sqrt{\rho_o max\left[0, p_r - p_{wb}\right]}\ and\ w_{ro} = r_{go}w_{ro} \tag{6}$$

C_{iv}, C_{pc} and C_{ro} are constants; u is the production choke setting ($u\epsilon\left[0,1\right]$); $\rho_{a,i}$ is the density of gas in the annulus at the injection point; ρ_m (oil/gas mixture) is the density of the production fluid at the well head; p_{wh} is the pressure at the well head; p_{wi} is the pressure in the tubing at the injection point; p_{wb} is the pressure at the well bore; p_s is the pressure in the separator and it is assumed constant; p_r is the reservoir pressure; r_{go} is the gas-oil ratio (based on mass flows, at actual conditions) of the reservoir fluids. The reservoir parameters are assumed to have very slow variations in comparison to the production dynamics and therefore are treated as constants. The valve specific function (f_{pc}), is used for the production choke. In order to control the opening of the gas lift valve, it is assumed that the same model is adequate.

$$f_{pc} = 50^{(u-1)} \tag{7}$$

The pressures are calculated through the ideal gas law, which is a very good approximation for the range of pressures involved in this simulation but for a real case scenario it would be necessary to include the compressibility factor (z). Besides, the pressure drops are assumed to be gravity dominated (friction is neglected). Therefore, it is not possible to make an analysis of gas lift optimization.

$$p_{a,i} = \left(\frac{RT_a}{V_aM} + \frac{gL_a}{V_a}\right)x_1 \tag{8}$$

$$p_{wh} = \frac{RT_w}{M}\frac{x_2}{L_wA_w - \frac{x_3}{\rho_o}} \tag{9}$$

$$p_{wi} = p_{wh} + \frac{g}{A_w}\left(x_1 + x_2\right) \tag{10}$$

$$p_{wb} = p_{wi} + \rho_o gL_r \tag{11}$$

And the densities can be calculated as follows:

$$\rho_{a,i} = \frac{M}{RT_a}p_{a,i} \tag{12}$$

$$\rho_m = \frac{x_2 + x_3}{L_wA_w} \tag{13}$$

Where M is the molar weight of the gas, R is the universal 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 acceleration due to gravity and ρ_o is the oil density, which is assumed incompressible.

The original model presented above was developed by Eikrem *et al.* (2008) and only slight modifications were performed. The gas lift valve model was modified for some special cases and they will be presented later on. The pressure drop due to friction could be considered in a simple way from the no-slip flow equations.

3. SIMULATION RESULTS

All parameters used in the simulations were taken from Eikrem (2006) and are presented in the following table. The parameter w_{gc} was considered to be ten times smaller than in the original work (Eikrem *et al.*, 2008) and the parameter C_r was introduced, which was considered to be equal to $12 \times 10^{-6}m^2$(Eikrem, 2006).

Table 1. Parameters of the simulation model.

Parameter	Value	Unit
M	0.028	kg/mol
R	8.31	J/kmolK
g	9.81	m/s^2
T_a	293	K
L_a	0.907	m
V_a	22.3×10^{-3}	m^3
ρ_o	1000	kg/m^3
p_s	1×10^5	Pa
w_{gc}	0.6×10^{-4}	kg/s
p_r	2.9×10^5	Pa
T_w	293	K
L_w	14	m
L_r	4	m
A_w	0.314×10^{-3}	m^2
A_r	0.314×10^{-3}	m^2
C_{iv}	1.60×10^{-6}	m^2
C_{pc}	0.156×10^{-6}	m^2
Cr	12×10^{-6}	m^2
rgo	0	-

3.1 Open Loop Non-linear Dynamical System

The equations are organized in a set of simultaneous first order differential equations, explicitly solved for the derivatives. There are no closed analytical expressions to such equations and therefore numerical integration must be performed. The simplest integration method is the Euler's, but the solution of this system was calculated with Scilab, which is an open source software package for scientific and numerical computing.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} f_1\left(x_1, x_2, x_3, u\right) \\ f_2\left(x_1, x_2, x_3, u\right) \\ f_3\left(x_1, x_2, x_3, u\right) \end{bmatrix} \tag{14}$$

It is possible to observe in Fig. 2 the dynamical behaviour of the states with respect to time. As pointed out by Equation (12), the pressure in the annulus at the injection point, $p_{a,i}$, is directly proportional to the mass of gas in the annulus, x_1, and when x_1 reaches a limit ($p_{a,i} > p_{wi}$) it falls abruptly because of the intense flow rate through the gas lift valve into the tubing. At the same rate that x_1 decreases, x_2 increases reducing the hydrostatic pressure in the tubing, lifting the liquid and thus reducing x_3. Then, x_1 becomes too low and the flow through the gas lift valve stops. During this period, the reservoir fills up the tubing up to the static level and the annulus is filled up with gas until the process is repeated over again.

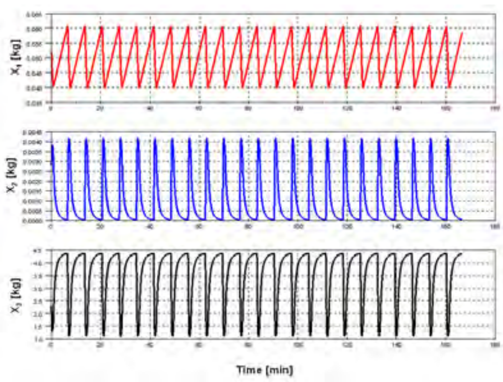

Figure 2. Resulting states of the system with respect to time.

Even though the casing-heading phenomenon can be understood through the analysis of the state variables it is somewhat unrealistic since this information is usually not available. The information that must be extracted from the open loop

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simulation is the oil production rate, which is taken as reference to evaluate whether or not the different strategies will be affordable.

Fig. 3 shows the production rates (total, gas and oil) and pressure (annulus, bottom hole and head) of a well under casing-heading. Differently from the oil production, the gas production is completely stopped at some intervals. These parameters are calculated for comparison purposes but not all of them are considered as inputs for the control system. Therefore, the average total (oil and gas) production under casing-heading phenomenon is $0.0689 kg/s$. The gas mass flow rate is practically negligible with respect to the oil mass flow rate.

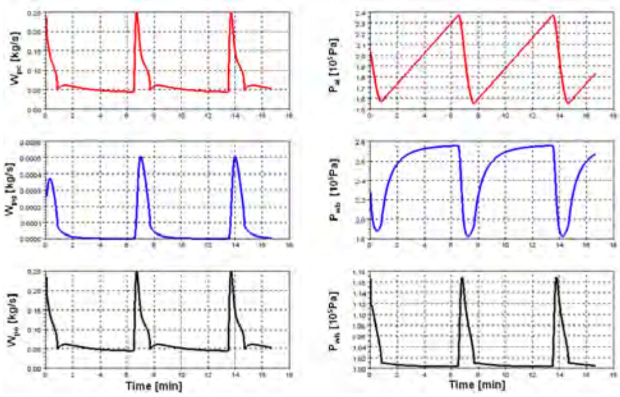

Figure 3. Production rates and pressures of a well under casing-heading.

The output function, Eq. 15, is a non-linear function of the states and the commanded input. This function represents the measured outputs and it is used as an input for the control system. In this work, the only measured output parameter used for control purposes is the bottom-hole pressure, Eq. 11.

$$y = g\left(x_1, x_2, x_3, u\right) \tag{15}$$

The study of the stability of the casing-heading can be performed with different combinations of variables from the mathematical model as long as they are independent, but it seems more straightforward to consider the state variables of the system.

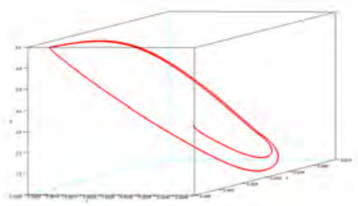

Figure 4. Three-dimensional representation of states' trajectories.

It is interesting to analyze the trajectories of the state variables with respect to each other as can be observed in Fig. 4, in which the states' trajectories form an orbit which is almost planar (or at least is in a twisted plane). The orbit remains in the same position after any number of cycles. From a mathematical point of view, the stability is analyzed in the sense of Lyapunov which says that if the forward orbit of any point in a small enough neighbourhood of it stays in a small neighbourhood the orbit, it is called Lyapunov stable. From an operational point of view, the stability is analyzed as the capacity of the downstream receiving facility and the process to handle the flow fluctuation (which is not considered in this work).

Studies revealed that the system could be represented by a two-dimensional approximation (Sinègre *et al.*, 2003), around a casing-heading set point, where the masses of oil and gas in the tubing are highly correlated. The limit cycle is analyzed for a planar dynamic system using the Poincarè-Bendixon criterion (Sinègre *et al.*, 2003) (Meglio *et al.*, 2009). This theorem says that if a bounding surface around a fixed point can be constructed so that all flux arrows on the surface are pointing towards the interior, and the fixed point in the interior is repulsive, then there must exist a stable limit cycle around that fixed point.

The correlation between the masses of gas and liquid in the tubing during casing-heading oscillation can be observed in Fig. 5. It can also be observed that the correlation is not perfect, but it is expected that it will not significantly affect the dynamical behaviour to assume some linear relation holds (Meglio *et al.*, 2009).

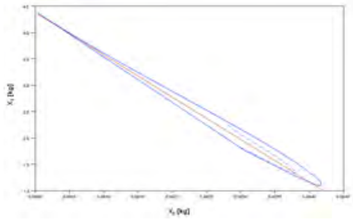

Figure 5. Mass of the liquid versus mass of the gas in the tubing.

The coefficients for the linear relation are obtained through Least Squares. Previous studies (Sinègre *et al.*, 2003) (Meglio *et al.*, 2009) demonstrated analytically the existence of a limit cycle in a gas lift well. The purpose of finding the linear relation, in this work, is to draw a two-dimensional phase portrait with the expected trajectories of the dynamical system and gain some insight about the existence of the limit cycle without rigorously proving its existence. In order to accomplish this objective, the following relation is used.

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix}f_1\left(x_1, x_2, ax_2+b, u\right)\\ f_2\left(x_1, x_2, ax_2+b, u\right)\\ f_3\left(x_1, x_2, ax_2+b, u\right)\end{bmatrix} \tag{16}$$

The phase portrait is created with the approximated the two-dimensional mathematical model in Eq. 16. The states' trajectory (Lyapunov stable orbit) is generated with the original three-dimensional mathematical model Eq. 1. Fig. 6 shows the relation between the orbit and the phase portrait, in which the arrows represent the derivatives at each point. It can be observed that the arrows inside the orbit point outside, which means that the fixed point inside must be repulsive. Following the arrows outside the orbit will bring the states approximately back to the orbit (because of the assumed linear dependence between two state variables), which characterizes a limit cycle oscillation. Although the applied method is not rigorous but insightful, it can be observed that any initial point (inside or outside the cycle) will eventually fall onto the orbit and stays there endlessly.

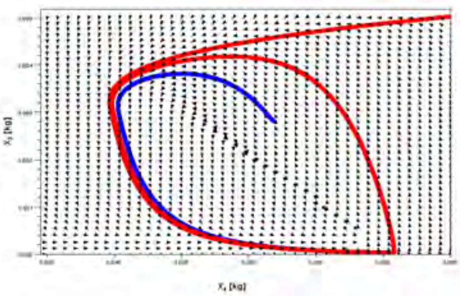

Figure 6. Two-dimensional phase portrait representing a limit cycle oscillation.

The classification of a casing-heading as an instability in a gas lift well was avoided because, from a mathematical standpoint, in this simplified model it is actually a stable phenomenon. It can be considered instability when its impact on the process equipment justifies such denomination or when linear stability theory is used to analyze the fixed points' stability.

3.2 Linearization of the Open Loop Dynamical System

There are at least two reasons to perform a linearization of the model at some point. The first one is to allow the use of linear control system design techniques to try to suppress the oscillations. The second reason is to evaluate the eigenvalues of the linearized system at a fixed point (inside the orbit, when there is one). According to the Poincarè-Bendixon criterion, a condition necessary to the existence of a limit cycle is that the fixed point in the interior of the orbit is repulsive and this characteristic is directly related to the eigenvalues of the linearized state matrix at the fixed point.

The minimum of this function is the point in which all derivatives are zero, in other words, exactly a fixed point, which was calculated as $x = [0.0518698\ \ 0.0021032\ \ 2.6121745]^T$.

The linearization procedure is based on the Taylor series expansion and the resulting linear system can be written by the following two equations:

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$$\begin{cases} \Delta\dot{X} = A\Delta X + B\Delta U \\ \Delta Y = C\Delta X + D\Delta U \end{cases} \tag{17}$$

Where X corresponds to a vector comprising all state variables, $\Delta Y = Y - Y_0$, $\Delta X = X - X_0$, $\Delta U = U - U_0$, Y_0 is the fixed point output variable, X_0 is the fixed point at which the linearization is performed and U_0 is a fixed equilibrium input. The linearized state matrix, also know as the Jacobian matrix.

The linearization was performed numerically because of the simplicity of the process, although some of the entries of the state matrix were also analytically calculated to validate the method.

Taking the Laplace Transform of Eq. 17 and performing some algebraic manipulations, the result is:

$$\Delta\dot{X}\,(s) = (sI - A)^{-1}\, B\Delta U\,(s) \tag{18}$$

This equation shows that the eigenvalues (λ) of the state matrix correspond to the open loop poles of the dynamical systems. The homogeneous response of a linear system can be written as follows:

$$y\,(t) = \sum_i C_i e^{\lambda_i t} \tag{19}$$

The coefficients C_i are determined from the given set of initial conditions. Thus, it can be inferred that if the real parts of all the eigenvalues (λ) are negative (positive) the response will decay with time and the system will be stable (unstable). The imaginary parts of the eigenvalues of the state matrix are responsible for the oscillatory behaviour of the state variables. Fig. 6 shows that the points inside the limit cycle are diverging, thus the eigenvalues are expected to have positive real parts. Moreover, the twisting behaviour of the states must correspond to non-zero imaginary parts of the linearized system, as shown in Tab. 2.

Table 2. Eigenvalues of the state matrix.

λ_1	-2.5121
λ_2	$0.0183 + 0.0326i$
λ_3	$0.0183 - 0.0326i$

Although the linear system has an analytic response, it was performed a numerical integration of the dynamical system to observe the resulting states. Fig. 7 shows the diverging and oscillatory behaviour of the states with respect to time, as it was expected.

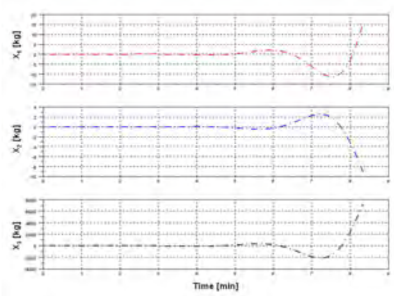

Figure 7. Resulting states of the system (linearized at a fixed point inside the limit cycle oscillation) with respect to time.

The diverging behaviour of the states can be observed in the phase portrait in Fig. 8. It means that the fixed point inside the limit cycle is repulsive and not that the non-linear system is unstable, since the linearization is only locally representative.

All analysis presented in this section refer to the reference dynamical system. It is expected that if some parameter is changed (choke setting or gas lift flow rate, for example) in such a way that the casing-heading is suppressed, the limit cycle will collapse into a stable fixed point and the respective eigenvalues of the linear state matrix will have negative real parts.

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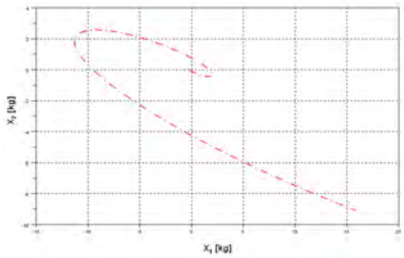

Figure 8. Two-dimensional plot of the states of the linearized system.

3.3 Production Choke Opening Effect

According to Hu and Golan (2005), choking is the most used pragmatic way of stabilizing unstable wells (or suppressing stable oscillations). The role of choking relies on the fact that a smaller choke opening can increase friction loss for the whole system (and even complicate the gas-flow rate through the gas lift valve). What is demonstrated in this section is that the static choking performed by operators can only stabilize the well at the cost of large production losses.

Using the techniques presented in the previous section, one linear model was obtained for each production choke opening in a discrete set ranging from 10 to 80%. The eigenvalues of the state matrices were calculated for each linear system and plotted in the complex plane. In Fig. 11 an open loop root locus with respect to the choke opening can be seen. The largest choke opening, corresponding to 80%, lies in the right of the figure and as the choke is being closed the eigenvalues move toward the left half s-plane where the linear system is stable.

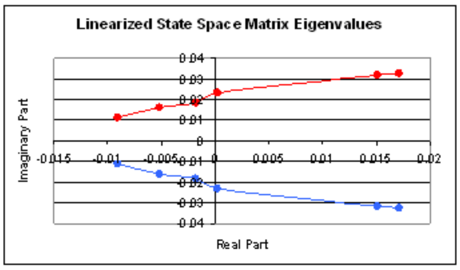

Figure 9. Eigenvalues of the linear system for different choke settings.

The crossing of the imaginary axis also represents the collapsing of the limit cycle (the fixed point is then attractive), which for this example occurs at 40%, as it is illustrated in Fig. 10.

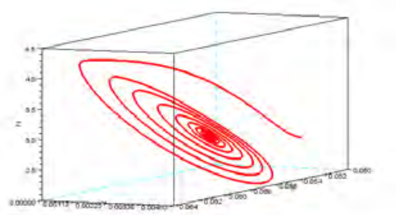

Figure 10. Collapsing of the limit cycle for a choke opening of 40%.

The average production over a long period (to damp the effect of initial conditions and cycles) was obtained for each choke opening and a curve was drawn (Fig. 11). Unfortunately, in order to completely suppress the production oscillation it is necessary to restrict the choke in such a way that the resulting production is almost half of the reference oscillating production, and unless extremely necessary it is obviously not recommended.

Therefore, it almost makes sense that when the downstream receiving facility can handle the flow fluctuations, one seldom has the motivation to deal with it (Hu and Golan, 2005). However, that is not the end of the issue, since Hu and Golan (2005) also affirmed that production loss is the norm for oscillating wells and instabilities (oscillations) have to be seriously treated even when they do not cause any operational problem.

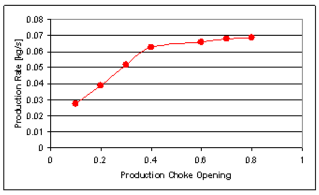

Figure 11. Production rate with respect to static choke opening.

3.4 Production Choke Control System Design and Closed Loop Simulations

Previous works (Hu and Golan, 2005) Storkaas (2005) (Eikrem *et al.*, 2008) argued that a feedback control could not only suppress the production oscillation but remedy the production loss as well. It might seem counter-intuitive to some people that by adding a restriction (or increasing the pressure loss) it would be possible to increase the production rate. The idea is that, despite the added pressure loss, the optimized use of the available gas could perform such a task.

Therefore, the objective of this section is to design a control system that can stabilize the production at the unstable fixed point inside the limit cycle and analyze the production rate. The only interest is to maintain the production conditions stable and as close as possible to the reference (not to have the best control or some common system structure).

A Linear Quadratic Gaussian (LQG) control was designed to achieve this goal. According to Skogestad and Postlethwaite (2005), the development of such control technique coincided with research programs to address problems such as rocket manoeuvring with minimum fuel consumption, which could be easily defined as an optimization. It assumes that the plant dynamics are linear and known, and that the measurement noise and disturbance signals are stochastic with known statistical properties (usually assumed to be uncorrelated zero-mean Gaussian stochastic processes with constant power spectral density matrices.

Therefore, the linearized system at the unstable fixed point inside the Lyapunov stable orbit is used by the control system design procedure. The response of this linear system was illustrated in Fig. 7 and it diverges and the objective is to stabilize it.

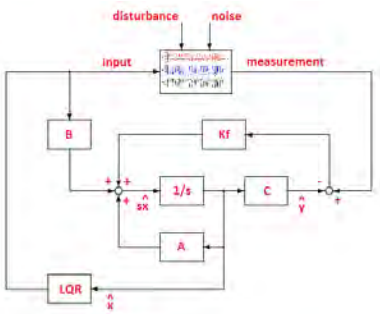

Figure 12. LQG controller and plant (Skogestad and Postlethwaite, 2005) - modified.

The control system designed guarantees that the linear closed loop system is stable and robust to some disturbances and noises. The fixed point that was previously repulsive is now stable. However, the main interest is not in the linear system but rather in the non-linear dynamical system. Fig. 13 shows the closed loop non-linear simulation and it is possible to observe the stabilization of the states, but in this case the control system is not so robust and minor disturbances can lead to a stable orbit (with smaller amplitudes than the original one). This is due to the limited small neighbourhood in which the linear system is a good approximation. With a little tuning it is possible to change this picture or another control system could be designed, but the objective is to measure the production rate in a stable condition and this is possible even with this poor controller.

The production rate at the stabilized condition is 0.0882 kg/s, 28% above the reference condition. Even though the adopted procedure to design a control system for the casing-heading was not very effective, it was possible to verify that the stabilized production by a feedback control system is higher than the oscillation production. This result is very interesting and confirms previous studies. It should also be noted that the design objective was to stabilize at a fixed point and not to achieve the greatest possible production.

3.5 Modification of the Gas Lift Valve Orifice Diameter

The feedback control system was able to enhance production and at the same time suppress the oscillations, but it created an additional pressure drop in the tubing. Therefore, it is interesting to come up with an alternative that has the same benefits without the added pressure loss in the tubing.

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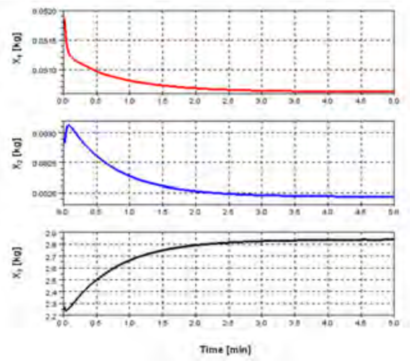

Figure 13. Resulting states of the closed loop linear system with respect to time.

According to Xu and Golan (1989) there are three independent devices that can regulate the production of gas lift wells and the nature of equilibrium: gas lift valve, surface production choke and surface injection choke. In this work it is assumed that the boundary condition is a constant gas lift flow rate at the surface (and not constant pressure), but it is reasonable that a control system (or at least a pressure control) in the injection choke could enhance the well production performance. The influence of the production choke has already been presented. Therefore, the immediate answer lies with the gas lift valve, which controls the discharging gas into the tubing. Therefore, the immediate answer lies with the gas lift valve, which controls the discharging gas into the tubing.

When a casing-heading occurs (Almeida, 2011) the gas flow through the operating valve is sub-critical and disturbances in production pressure cause changes in gas flow rate, and thus the gas flow dynamics in the casing-tubing annulus are linked with the tubing flow dynamics. Besides that, when the tubing pressure increases the gas flow rate through the orifice valve is reduced, which causes an increase in the hydrostatic pressure increasing even more the tubing pressure, thus perpetuating this process (depending on the annulus pressure variation).

The dynamical model considered in this work uses a simplified gas lift valve Eq. 2, which is an approximation for the sub-critical flow. Roughly, the critical flow can be modelled by truncating the maximum flow rate at the critical ratio, which would predict qualitatively the gas lift valve performance.

It can be observed in Fig. 14 two performance curves for gas lift valves generated with Eq. 2. The valve used in the reference model allows a large gas flow rate. According to Hu and Golan (2005) a valve with smaller port size can increase stability since it can suppress large flow variations. Thus, in order to avoid oscillations it is necessary to restrict the flow and a valve with a smaller orifice was generated.

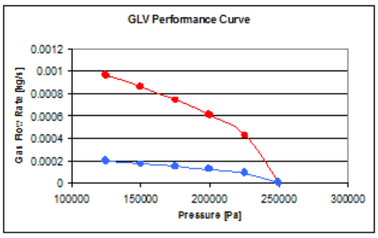

Figure 14. Approximated conventional gas lift valve performance curve.

Even when the gas flow through a conventional orifice gas lift valve is sub-critical, it is possible to suppress the oscillation. The gas lift valve plays a very important role in the production by gas lift and the determination of the best performance for a given production system is fundamental. The resulting stabilized production rate was 0.093 kg/s, 35$ higher that the reference production rate. The results obtained could be quantitatively different for a different boundary condition, but it would not be qualitatively modified.

Another approach is to assure in some way that the flow through the gas lift valve is always critical. The advantage is that the gas flow rate is constant irrespective of any pressure fluctuations in the tubing. The venturi-nozzle gas lift valve has a critical flow of 0.9 or higher, thus it can be inferred that it operates almost exclusively under critical flow. Replacing an orifice valve with a venturi one can increase enormously the gas flow rate if the throat areas are the same (Almeida, 2011). It must be noted that the throat area of the venturi-nozzle gas lift valve must be wisely chosen in order to stabilize production.

3.6 Proportional Response Gas Lift Valve

(Almeida, 2011) comments that two types of gas lift valves are typically used in the oil and gas industry. In the

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previous section, only valves that were always open (in the casing-to-tubing direction) were considered. The second type uses a mechanism, usually a charged bellows, to open or close the valve according to wellbore pressure or temperature. This section presents a specific type of charged bellows gas lift valve.

Differently from the conventional orifice gas lift valve, for stability purposes, it would be interesting to have a gas lift valve performance curve with a positive slope. This would mean that for any increase in the tubing pressure the gas flow rate through the gas lift valve would also increase causing a reduction in the hydrostatic pressure inside the tubing.

According to (Alhanati *et al.*, 1993), in order to stabilize a gas lift well, a procedure that can be implemented is to set the gas lift valve to operate within the throttling close region of the operating valve's throttling flow performance. A valve designed to perform such a task is the Proportional Response gas lift valve, which has a larger ball and seat area to have its response dominated by the tubing pressure, especially when the annulus pressure is almost constant.

A simplified model of the proportional response Gas Lift valve was developed according to the following equation:

$$w_{iv} = max\left\{0, \frac{(p_{ai}-p_{wi})}{|p_{ai}-p_{wi}|}\frac{(p_{ai}-p_{ai-CLOSE})}{(p_{ai-OPEN}-p_{ai-CLOSE})}max\left[0, Ap_{wi}+B\right]\right\} \tag{20}$$

Where the parameters $P_{ai-CLOSE}$, $P_{ai-OPEN}$, A and B are set according to the desired valve calibration. The simplified model developed for the Proportional Response gas lift valve is illustrated in Fig. 15, where it can be compared to the gas lift valve curve in the reference model. It is interesting to note that it allows high gas flow rates for some conditions, but its slope is responsible for a stabilizing effect. Despite its simplicity, the qualitative behaviour is similar as of the complex model. The closing pressure did not change in the simplified model, but it should not affect the attained stabilization. A slight modification can be made in the equation to consider this variation.

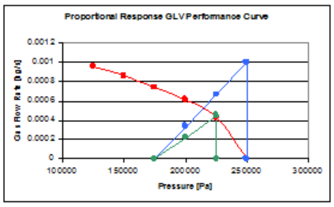

Figure 15. Simplified Proportional Response gas lift valve performance curve.

The Proportional Response gas lift valve is able to stabilize the productions, confirming the recommendation made by (Alhanati *et al.*, 1993). There are, however, differences with respect to operational and reliability issues in comparison with a typical orifice gas lift valve that must also be considered prior to decide for a definitive solution. The resulting production was 0.093 kg/s, 35% higher than the oscillating production.

3.7 Electric Gas Lift Valve

In this work it was shown that there are several different valves that can stabilize production and that by only adjusting the orifice diameter it could attenuate production oscillations. Schnatzmeyer *et al.* (1994) presented a prototype of a different kind of gas lift valve, the surface-controlled electric gas lift valve, which if it could only have a statically adjustable orifice area would already be enough for the casing-heading issue. The reliability of such a valve would have to be at least comparable to other wells equipment.

The objective of this section is to show that if the electric gas lift valve could be controlled as a production choke, it would be possible to design a control system to suppress the production oscillations. Even though it would not be interesting for the casing-heading as it was presented in this work, the concept could possibly find applications in more complex situations.

Differently from changing the valve, the idea was to stabilize the production at approximately the reference fixed point. If the idea was to change the valve's characteristics, it would fall in the cases presented previously because it would change the dynamical system in a way the fixed point is stable and at a different location in the phase-portrait. Therefore, the resulting production is not expected to be comparable as the objective was not to maximize production.

A very similar approach to the production choke control system design was performed for the electric gas lift valve. The same control valve specific function was assumed, the same control structure was assumed and also the same sensor. A new linear dynamical model was generated for this new system configuration.

A slight authority reduction was imposed in the designed control system due to numerical stability issues and for the non-linear dynamical system it was not entirely satisfactory in terms of performance, but it could stabilize the production and that was its main goal. Therefore, it did not stabilize the production at the same fixed point as the choke control did. The production achieved with this system was 0.0928 kg/s, 35% higher than the reference. It is different from the stabilized condition of the production choke mainly due to the authority modification imposed on the changed the fixed point in this case.

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4. CONCLUSIONS

The investigation has used a simplified model that can be adjusted to match physical response of a well within a range of variation of the parameters. The main objective was to show that the oscillating well behaviour results in production losses that can be mitigated by different strategies.

The costs of implementing any strategy to suppress oscillations are usually available, but they are not of great use alone. It is fundamental to determine the impact on production rate to compare the alternatives and choose the most profitable one, despite the implementing costs.

The results in terms of production rates for different strategies were calculated and it was possible to observed that the oscillating production present losses when compared to any of the strategies presented in this work (except the static closure of the production choke that causes even higher production losses). Even though the model is very simple, it can reflect the qualitative behaviour of each parameter. Therefore, it would be necessary to perform a similar procedure as presented by this work with a more complex and representative model.

Gas lift flow rate and productivity index were considered as constants in this work, but these parameters could be modified in practical situations (changing in compression train and intervention). Hu and Golan (2005) showed that productivity index has a stabilizing effect since it compensates the hydrostatic pressure reduction by adding fluid (and can also increase production). They also showed that increasing gas injection rate would also increase stability, because it increases production and makes the gas in the annulus stiffer. (Alhanati *et al.*, 1993) affirmed that a reduction in the annulus volume could also have a stabilizing effect. All these factors could be qualitatively analyzed with the simple model presented by just adjusting one parameter at a time.

There are other situations in which production oscillation can occur, such as terrain induced slugging and dynamic gas conning formation for example. These other phenomena were not addressed in this work but some of the strategies developed here could also be used (active control) to suppress them.

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