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THE INFLUENCE OF AN OSCILLATING OIL WELL IN THE PRODUCTION SYSTEM

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Abstract. *When an oil production well is oscillating, as in casing heading or severe slugging situations, its daily average production rate is decreased. Such oscillations are well known, easily characterized in average and suppression strategies have already been discussed in the literature. It can also be observed that the production of an oscillating well can increase flaring and it can also cause inefficiencies in the separation process. Besides that, these oscillations might instantaneously increase the three-phase separator vessel pressure until it returns to the set point reference pressure, by the actions of the automatic control system. This work aims to evaluate the impact of the separator vessel pressure variations in the production of the other non-oscillating wells connected to the same production header. It is also interesting to observe that when the downstream (separator) boundary conditions for each well is of constant pressure in a transient simulation, it is impossible to capture some oscillations caused by the dynamic coupling of different wells in the same header and the separator vessel. A non-linear simplified model that is able to capture the Casing-Heading in a Gas Lift well is presented. It is considered that the gas flow through the gas lift valves is sub-critical, which preserves the dynamic coupling between the annulus and the tubing. It is also presented a three-phase separator vessel dynamic model, with simplified control systems acting on the outflow gas, water and oil valves to maintain pressure, liquid level and water level within a tolerable range. These control systems are also important to avoid entrainment of liquid in the gas outflow. In the integrated model, the separator pressure is the downstream boundary condition to all the production wells attached to the same header. Some situations were evaluated with the model, one of which combines in the same header a stable well and an oscillation well. It can be observed that when isolated (constant pressure downstream boundary condition), the oscillating well follows a limit cycle with a well defined fundamental frequency, with several harmonics. It is possible to evaluate the "stability" of such oscillating well by the evolution of the linearized model eigenvalues. However, when the complete system is analyzed, it can be observed that the stable well might begin to oscillate with significant energy distributed in the harmonics different from the fundamental frequency of the originally oscillating well. The oscillating well is also affected; its trajectory is no longer a limit cycle but a higher dimensional chaotic non-linear phenomenon. In some particular situations, some cycles can even be completely suppressed and return to normal afterwards. Therefore, this work evidences the negative influence of a well's instability in the production of other wells connected to the same production header. It is also shown that when a downstream boundary condition of constant pressure is considered, it is impossible to simulate several transient phenomena caused by the dynamic coupling of different production system's elements. A control system is proposed to suppress the Casing-heading to minimize the impact in the processing plant and also minimize production losses.*

Keywords: *Gas Lift Stability, Process Equipment, Limit Cycle, Control Systems*

1. INTRODUCTION

The present work considers a gas-lift system in which the injected gas interacts with the production flow in a way that it causes cyclic variations in pressure and production rate under certain operating conditions. Casing-heading and pipeline/riser slugging are two of the most frequent oscillations that interact with gas lift systems. Both phenomena are caused by build-up of gas mass within the system and can be controlled by applying a pressure drop among several other different possible strategies.

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.

Besides that, this cyclic production is characterized by alternating high liquid production with high has production (eventually also with no production periods). The high liquid flow rate period might cause a separator shutdown due to high liquid level if the liquid outflow is unable to balance the liquid inflow.

Just after this high liquid production comes the high gas production which pressurizes the production separator to a point that can also cause a shutdown. Even when the vessel is able to continue the operation, this cyclic gas production causes a cyclic separator pressurization and consequently might negatively affect other wells hydraulically connected to the same production header, causing production losses among other effects.

It is a common belief in the industry that this cyclic pressure variation of the separator is of a low amplitude and it can be completely neglected even in transient simulations. Despite that belief, the authors, while optimizing the production of Gas Lift wells in a FPSO operating in the Campos Basin, were faced with some oscillations that could not be characterized as the classical severe slugging or casing heading.

One of such a situation was an oscillatory bottom-hole pressure which was being previously considered as measurement noise and its main frequency (most energetic harmonic frequency) was almost two times higher than any other fundamental frequency in the system (other well subject to severe slugging). During production tests, when the well was connected alone to the test separator, these oscillations disappeared and the production was steady.

It seems reasonable, at least from a linear world perspective, to assume the cyclic separator pressure variations caused by severe slugging, for example, would respond at the same frequency as slugging. Therefore, an engineer analyzing a production system with several wells connected to the same header, with only one experiencing severe slugging, might be lead to conclude that oscillations present in different wells with different oscillation frequencies would not have a common cause.

Another situation observed in the field was that of a well experiencing severe slugging but interestingly some of its cycles were completely suppressed without any external action and then the oscillations would start again. Both these situations were captured by transient simulations by coupling the separator dynamics in the system.

Therefore, this work evidences the negative influence of a well's instability in the production of other wells connected to the same production header. The main contribution of this work though is that it shows that when a downstream boundary condition of constant pressure is considered, it is impossible to simulate several transient phenomena caused by the dynamic coupling of different production system's elements and the non-linear nature of the system dynamics associated with it high order can cause some chaotic behaviour.

The simulations performed in this work are based on the model for Gas Lift wells developed by Eikrem *et al.* (2008), which is basically a lumped parameter hydraulic model, and the three-phase separator model developed by Pinto (2009), which is also a lumped parameter model (flash calculations were not performed in this work).

This approach was chosen by its simplicity and it also did not require any commercial software to show the observed phenomena. Precise transient simulations of oil fields today require commercial software that already are able to integrate production wells and processing facilities. Therefore, besides the instructional purpose, the applicability of these simplified dynamic models is limited to control system and state observer design.

2. ANALYSIS OF AN OSCILLATING WELL

A simple model was developed Eikrem *et al.* (2008) based solely on the conservation of mass principle and it has the capability capturing the main dynamics of casing-heading qualitatively. Consider a model represented in Fig. 1, which for each well 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 (other control strategies could be applied, as constant pressure for example). Outflow can be regulated by the production choke.

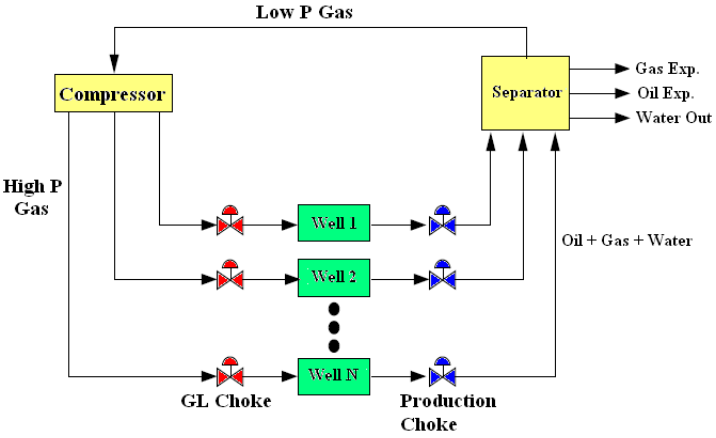

Figure 1. Gas-Lift Oil Well (Nakashima, 2004) - modified.

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

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

where w_{gc}^i is a constant mass flow rate of gas into the annulus, w_{iv}^i is the mass flow rate of gas through the gas lift valve, w_{rg}^i is the mass flow rate of gas from the reservoir into the tubing, w_{pg}^i is the mass flow rate of gas through the production choke, w_{ro}^i is the flow rate of oil from the reservoir into the tubing, and w_{po}^i is the mass flow rate oil through the production choke.

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 production bottom-hole pressures and its corresponding production rates, is also considered as a simplified valve equation.

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

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.

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

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

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

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

$$w_{ro}^i = r_{go}^i w_{ro}^i \tag{7}$$

where C_{iv}^i, C_{pc}^i and C_{ro}^i are constants; u^i is the production choke setting ($u^i \epsilon \left[0, 1\right]$); $\rho_{a,i}^i$ is the density of gas in the annulus at the injection point; ρ_m^i (oil/gas mixture) is the density of the production fluid at the well head; p_{wh}^i is the pressure at the well head; p_{wi}^i is the pressure in the tubing at the injection point; p_{wb}^i is the pressure at the well bore; p_s^i is the pressure in the production header, which is assumed to be the separator pressure and generally it is assumed constant for well's simulations (in this work, only one production header is considered and $p_s^i = p_s$ but not necessarily constant); p_r^i is the reservoir pressure; r_{go}^i 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.

The pressures are calculated through the ideal gas law, 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.

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

$$p_{wh}^i = \frac{RT_w^i}{M}\frac{x_2^i}{L_w^i A_w^i - \frac{x_3^i}{\rho_o^i}} \tag{9}$$

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

$$p^i_{wb} = p^i_{wi} + \rho^i_o g L^i_r \tag{11}$$

And the densities can be calculated as follows:

$$\rho^i_{a,i} = \frac{M}{RT^i_a} p^i_{a,i} \tag{12}$$

$$\rho^i_m = \frac{x^i_2 + x^i_3}{L^i_w A^i_w} \tag{13}$$

where M is the molar weight of the gas, R is the universal gas constant, T^i_a is the temperature in the annulus, T^i_w is the temperature in the tubing, V^i_a is the volume of the annulus, L_a is the length of the annulus, L^i_w is the length of the tubing, A^i_w is the cross sectional area of the tubing above the injection point, L^i_r is the length from the reservoir to the gas injection point, A^i_r is the cross sectional area of the tubing below the injection point, g is the acceleration due to gravity and ρ^i_o is the oil density, which is assumed incompressible.

Table 1. Parameters of the simulation well models.

Parameter	Value for Well 1	Value for Well 2	Unit
M	0.01648	0.01648	kg/mol
R	8.31	8.31	$J/kmolK$
g	9.81	9.81	m/s^2
T_a	303	303	K
L_a	2400	2400	m
V_a	37.68	37.68	m^3
ρ_o	781	781	kg/m^3
w_{gc}	0.6×0.55	0.6×0.09	kg/s
p_r	1.5×10^7	1.5×10^7	Pa
T_w	303	303	K
L_w	2400	2400	m
L_r	150	150	m
A_w	0.00316	0.00316	m^2
A_r	0.00316	0.00316	m^2
C_{iv}	2×10^{-4}	2×10^{-4}	m^2
C_{pc}	2×10^{-3}	2×10^{-3}	m^2
Cr	1.992×10^{-6}	1.992×10^{-6}	m^2
rgo	0.1	0.1	-
BSW	0.1	0.1	-

This work analyzes the influence of the oscillatory production of one well into another hydraulically connected to the same production header. To simplify, only two wells are considered (the parameters are taken from (Texeira, 2010) and they are presented in Tab. 1) and they are almost identical, although could also be very different. The gas flow rate of one of the wells is purposefully reduced until its production becomes oscillatory, as can be observed in Fig. 3.

Besides that, one extremely important information used in production supervising to determine the causes of undesired behaviour in the well is the bottom-hole flowing pressure (P_{wf}), when Permanent Downhole Gauge (PDG) is available. The state x_3 can be directly related to P_{wf} and the curve which x_3 described in Fig. 3 is the signature for Casing Heading/Severe Slugging phenomena.

The trajectories of the state variables can be analyzed in a plot with respect to each other as can be observed in Fig. 3, in which the states' trajectories form an orbit. The orbit remains in the same "track" after any number of cycles and by doing that the repeated cycles are exactly the same, at least for this extremely simple model (the separator pressure is considered constant).

3. THREE-PHASE SEPARATOR

Surface facilities are responsible for oil-water-natural gas separation and treatment to meet sales and/or pipeline specifications. The first step of this process takes place at three-phase separators, equipment that employ basically gravity settling mechanism. Figure 4 shows schematically a three-phase separator and its main control systems.

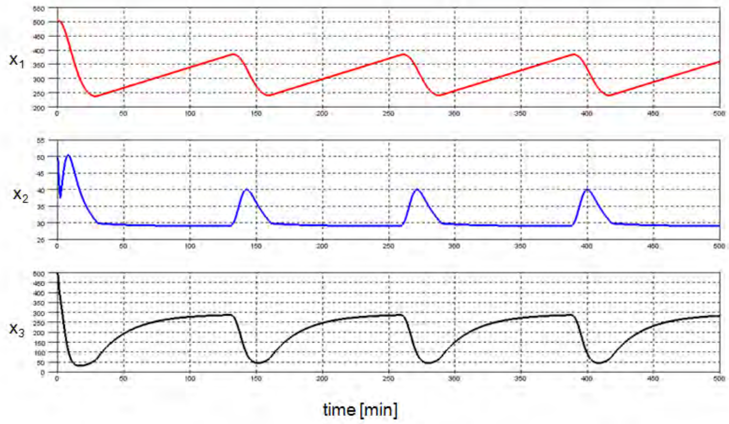

Figure 2. Resulting states of the system with respect to time.

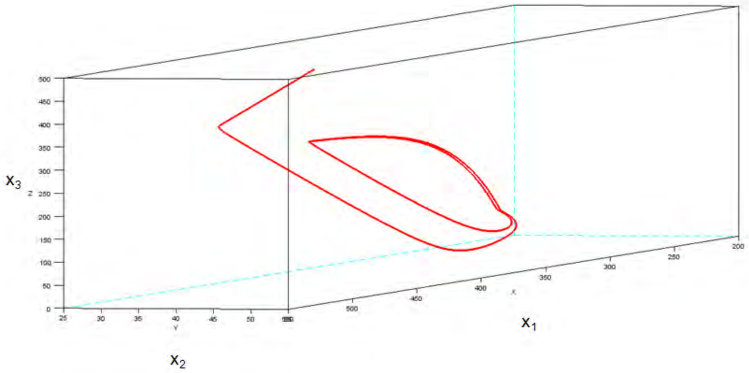

Figure 3. Three-dimensional representation of states' trajectories.

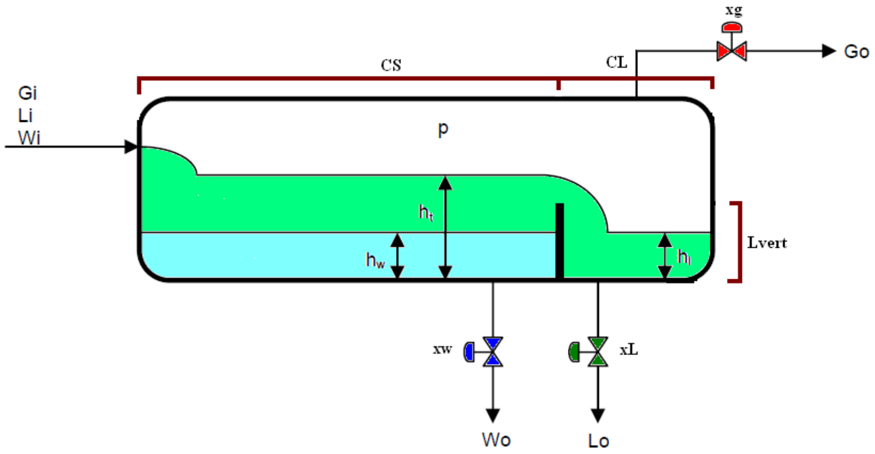

Figure 4. Three-phase separator.

Water-oil separation is mainly performed in the section before the down-comer, the gravity settling section. Oil-water interface level is essential to guarantee appropriate residential time to water-in-oil and oil-in-water separations. An interface level controller senses the height of the oil-water interface, sends a signal to the water outlet valve maintaining the desirable amount of water into the vessel. An inefficient control causes poor separation and consequent oil into water and water into oil carry-over and affect the downstream processes.

The weir is responsible for collecting the separated oil. The height of the oil in this chamber controls the liquid level in the vessel. Low level could result in gas into oil carry-over, damaging pumps and interfering in oil treatment.

Since liquid-gas interface normally is maintained at 50% of the vessel diameter, the upper cross-sectional area is designed to gas horizontal flow. The gas outlet valve is responsible for pressure vessel control, and an inefficient control may cause a increase in well back-pressure, compromising well production. Otherwise, well slugging affects pressure controller performance, affecting oil production and natural gas treatment.

The efficiency of this separation depends on hydrodynamic and thermodynamic parameters, particularly pressure and temperature, which are normally design parameters, and residence time which is related to the appropriate operation of the control system.

In order to properly describe the dynamic behaviour of these vessels, it is defined a set of ordinary equations considering three feedback controlling actuating in the water, oil and natural gas outlet valves. These equations are based merely in mass balance and controller equations with a similar approach that was presented in the previous section for gas lift wells' modelling.

3.1 Separator Dynamic Modelling

Pinto (2009) develops a model for the three-phase separator which has four state variables: the separator pressure P; the total liquid height in the water-oil separation compartment h_T; the water liquid height in the water-oil separation compartment h_w; and the oil height after the down-comer h_L. The total liquid level(h_t) is calculated considering oil (L) and water (W) inlet and outlet mass flow rates according to Eq. 14.

$$\frac{dh_T}{dt} = \frac{L_i + W_i - W_o - L_v}{2C_S\sqrt{h_T(D-h_T)}} \tag{14}$$

Where C_S is the length of the water-oil separation compartment and D is the diameter of the separator and L_v is the oil outflow into the C_L compartment through the down-comer.

During normal operating conditions, the C_L compartment (C_L is the length of the oil compartment, according to Fig. 4) is filled with oil only and thus only oil mass balance is performed. It must be observed that the oil height in this compartment does not exceed the liquid height in the C_S compartment, resulting in the following state equation:

$$\frac{dh_L}{dt} = \begin{cases} \frac{L_v - L_o}{2C_L\sqrt{h_L(D-h_L)}} & \text{if } h_T > h_L, \\ \frac{dh_T}{dt} & \text{if } h_T \leq h_L \end{cases} \tag{15}$$

The water mass balance in the C_S compartment is performed in the same way resulting in:

$$\frac{dh_w}{dt} = \frac{W_i - W_o}{2C_S\sqrt{h_w(D-h_w)}} \tag{16}$$

The separator pressure P is related to the total mass of gas contained in the vessel. The state equation for the pressure is derived from a gas mass balance ($G_i - G_o$) associated with an ideal gas state equation, resulting in:

$$\frac{dP}{dt} = \frac{P\left(L_i + W_i + G_i - L_o - W_o - G_o\right)}{V_T - V_{CS} - V_{CL}} \tag{17}$$

Where V_T is the total vessel volume.

The liquid volume (oil and water) in the C_S compartment is given by:

$$V_{CS} = C_S\left[\left(\frac{D^2}{4}\right)\cos^{-1}\left(1 - \frac{2h_T}{D}\right) - \frac{1}{2}\left(D - 2h_T\right)\sqrt{h_T\left(D - h_T\right)}\right] \tag{18}$$

The oil volume in the C_L compartment is given by:

$$V_{CL} = C_L\left[\left(\frac{D^2}{4}\right)\cos^{-1}\left(1 - \frac{2h_L}{D}\right) - \frac{1}{2}\left(D - 2h_L\right)\sqrt{h_L\left(D - h_L\right)}\right] \tag{19}$$

The water volume in the C_S compartment is given by:

$$V_{CSw} = C_S\left[\left(\frac{D^2}{4}\right)\cos^{-1}\left(1 - \frac{2h_w}{D}\right) - \frac{1}{2}\left(D - 2h_w\right)\sqrt{h_w\left(D - h_w\right)}\right] \tag{20}$$

The oil volume in the C_S compartment is calculated by the difference between the total liquid volume and the water volume in the C_S compartment, which means:

$$V_{CSL} = V_{CS} - V_{CSw} \tag{21}$$

The oil flowrate that leaves the C_S compartment into the C_L compartment is modelled as an open channel flow through a spillway with the following equation:

$$L_v = 0.415\sqrt{2g}\left(C_{VERT} - 0.2\max\left\{0,\left(h_T - h_{VERT}\right)\right\}\right)\left(\max\left\{0,\left(h_T - h_{VERT}\right)\right\}\right)^{\frac{3}{2}} \tag{22}$$

Where g is gravity acceleration, h_{VERT} is the spillway height and C_{VERT} is given by:

$$C_{VERT} = 2\sqrt{h_{VERT}\left(D - h_{VERT}\right)} \tag{23}$$

The mass inflow rate of gas, oil and water is the total production of the wells connected to the separator's header. The outflow is calculated as unidirectional valve models (check-valves) considering the downstream pressure constant, which is a simplification since no other process equipment is modelled in this work.

The oil outflow rate is (exiting from the C_L compartment):

$$L_o = 2.4028 \times 10^{-4} C_v^{MAX} x_L \max\left\{0, \sqrt{\frac{P - P_L + \rho_L g h_L \times 10^{-5}}{\frac{\rho_L}{\rho_{H_2O,15.5^oC}}}}\right\} \tag{24}$$

Where P_L is the downstream pressure for the oil flow path, x_L is the opening of the outflow choke (which is a control variable). It is interesting to observe that the hydrostatic pressure inside the vessel is also taken into account with the term $\rho_L g h_L$.

The water outflow rate is (exiting from the C_S compartment)

$$L_w = 2.4028 \times 10^{-4} C_v^{MAXw} x_w \max\left\{0, \sqrt{P - P_w + \left(\rho_w g h_w + \rho_L g\left(h_T - h_w\right)\right) \times 10^{-5}}\right\} \tag{25}$$

Where P_w is the downstream pressure for the water flow path, and x_w is the opening of the outflow choke (which is a control variable).

For the gas outflow rate, a simplified model is used that approximates the correct behaviour for sub-critical gas flow through chokes (critical flow is not taken into account in this work). G_o is then calculated via:

$$G_o = 2.881 \times 10^{-4} C_V^{MAXG} x_G \max\left\{0, \frac{\left(P - P_G\right)\left(P + P_G\right)\frac{M_{air}}{M_{gas}}}{P^2}\right\} \tag{26}$$

Where P_G is the downstream pressure for the water flow path, and x_G is the opening of the outflow choke (which is a control variable).

Table 2. Parameters of the three-phase separator simulation model.

Parameter	Value	Unit
D	3	m
C_S	5	m
C_L	3	m
h_{VERT}	1.5	m
P_L	8	bar
P_G	8	bar
P_w	8	bar
C_V^{MAXL}	3×1025	m^2
C_V^{MAXw}	410	m^2
C_V^{MAXG}	120	m^2

3.2 Simplified Separator Control System

Separators are equipment present in most offshore production facilities and they are designed to separate and remove the free water from the mixture of crude oil and water. According to Mendes *et al.* (2012), the three-phase separator is basically designed to separate the multiphase fluid and also to damp the load oscillation that comes from well. Theoretically, a control system for this process would allow the oil production optimization and reduction of the quantity of residual oil in water. Therefore, it is expected that the separator control would allow good separation efficiency and also to filter out disturbances.

Mendes *et al.* (2012) point out that in normal operation the desired separation of the three phases is obtained maintaining the separator state variables at the operating point. However, when high amplitude input flow oscillations affect the process, the vessel control has to be used to avoid the transmission of these flow oscillations to the output, which affects the efficiency of the downstream processes.

Although the negative influence in the downstream process is of great importance, our objective in this work lies in the upstream production system. It is important to notice that the production and process systems are (obviously) highly coupled and the analysis and design of the equipment should be done in an integrated way.

In this work, the simplest conceivable control system for the three-phase separator is used: the proportional controller (which admits steady state error). Not only that, but the control gain was not optimized and was chosen by a proposed rule of thumb in the same way for each state variable.

Therefore, only the separator pressure P control strategy is presented. The pressure is regulated by the gas mass outflow: if it is necessary to increase the vessel pressure, the gas outflow choke opening (x_G) must be reduced; if the vessel pressure is high, gas must be removed and the gas outflow choke opening must be increased.

The choke setting is defined for the next time step as a function of the previous time step setting, according to the following equation:

$$x_G^{t+\Delta t} = \left(1 + G_P\right) x_G^t \tag{27}$$

Where G_P is given by:

$$G_P = \min\left\{1, \max\left\{-1, \left(\frac{1}{P_{REF}}\right) P - 1\right\}\right\} \tag{28}$$

This control should not be used in real applications for several reasons and it is only designed to allow the separator to operate in a relatively controlled operational range in such a way that the coupled simulation is possible. It could be argued that the simplicity of such control system would be responsible for the observed dynamic coupling between different wells, but the coupling has been observed in offshore production systems with more complex controllers.

4. WELLS-SEPARATOR DYNAMIC COUPLING

The complete system will encompass the separator's state variables (h_T, h_L, h_w and P), and the i^{th} well's state variables (x_1^i, x_2^i and x_3^i). It is important to remember that the downstream boundary condition for each well is the separator pressure, which is now a state variable. The total mass inflow into the separator is the sum of the production rates of every well, which is calculated from the state variables.

Therefore, the complete state vector can be written as:

$$\vec{x}^T = \left[h_T,\, h_L,\, h_w,\, P,\, x_1^1,\, x_2^1,\, x_3^1,\, x_1^2,\, x_2^2,\, x_3^2\right]^T \tag{29}$$

And the non-linear state space representation remains:

$$\dot{\vec{x}} = \vec{f}\left(\vec{x}, \vec{u}\right) \tag{30}$$

Where $\vec{u}$ is the vector comprising all the control variables, which for the basic system consists only of the outflow chokes of the three-phase separator (x_G, x_L and x_w). Whenever an anti-slug control system or casing-heading suppression control system is active in the model, the vector $\vec{u}$ must be modified.

Only with an integrated production-processing model it is possible to capture the hydraulic coupling between different wells. In fact, the dynamic behaviour of the separator itself can alter the reservoir inflow response at some degree. The first parameter that the engineer evaluates is the P_{wf} and, depending on the production field, there might not be too many pressure gauges and decisions must be made with the information available. Sometimes the conclusion is quite straightforward, but sometimes the P_{wf} signature is not a "book example". Thus, a couple of examples are analyzed below.

4.1 Case 1 - Oscillatory and Stable well

The first case presented is exactly the same case shown in Fig. 2 (Well 1), but this time the separator pressure is not constant any more. Besides that, a second well (Well 2) is connected to the same production header. Well 2 is operating in a stable condition and if the downstream pressure (separator) is fixed, it reaches a steady-state without any oscillation.

The interest lies in the integrated system and the operational parameters of Well 1 is presented in Fig. 5. First of all, the P_{wf} (or equivalently P_{wb}) has not the same format as x_3 in Fig. 2, it has some deformation.

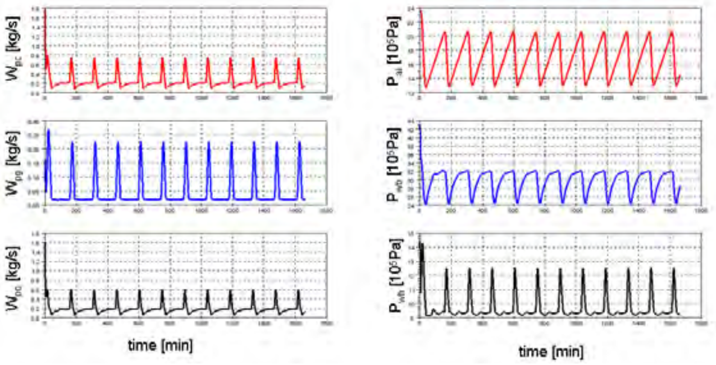

Figure 5. Well 1 operational parameters.

Nevertheless, it is clear that Well 1 experiences some sort of Casing-Heading. Observing only P_{wf}, it can be inferred that some accumulation of energy as pressure (fluid capacitance) followed by a liberation (increased production and increased gas injected through the gas lift valve) is occurring in this well. If the annulus pressure was constant it could be severe slugging, but the annulus pressure measurement enhances the confidence in the diagnostics. Some wells experience simultaneous Casing-Heading and severe slugging, but these cases are not treated here.

Well 2 should be stable, without any kind of oscillations according to the conventional transient simulation with constant separator pressure, but the actual result is presented in Fig. 6. The P_{wf} signature does not correspond to any classical oscillatory well behaviour and, in this extremely simple example, the bottom-hole pressure begins to behave in a somewhat noisy manner. In higher dimensional systems, this noisy (chaotic) behaviour is even more explicit.

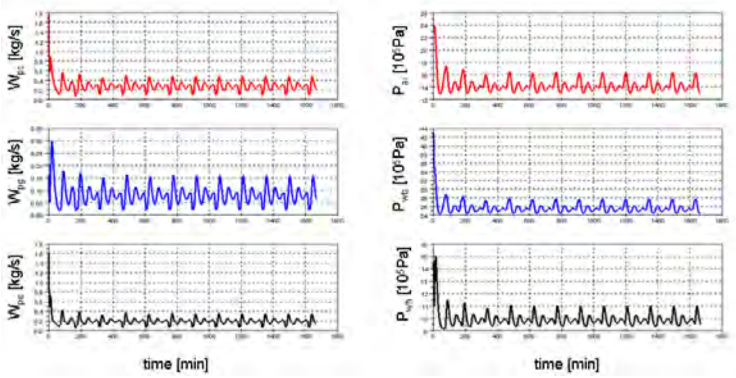

Figure 6. Well 2 operational parameters.

It can be observed (by inspection in time domain or by a frequency domain analysis) that there are peaks in a frequency close to the frequency of Well 1, which might indicate a possible common cause. A little more striking than that is the fact that there are relevant energy in other frequencies and eventually (depending on the system) it might also disguise the fundamental frequency hiding the correlation with the real cause. Besides, the engineer is expecting a constant behaviour and can be deceived to conclude that the measurement is erroneous when in fact the problem is the hydraulic coupling that is even causing production losses. The picture is even harder in a more complex system.

The three-dimensional plot of the state variables of Well 2 is presented in Fig. 7, with a restricted simulated time interval. If the engineer would take a long time interval from the sampled plant information, she or he would observe a cloud of points making it difficult to capture any pattern. It can also be observed that this behaviour is a little more complex than that observed in Fig. 3 since Fig. 7 shows a trajectory that is clearly not a limit cycle.

Actually, only Well 1's state trajectories were supposed to follow a limit cycle, since Well 2 was predicted to be stable (non-oscillatory). But by coupling the production system, Well 1 also modifies its own characteristics, although approximately remaining almost in its original limit cycle. The modified states' trajectory can be observed in Fig. 8.

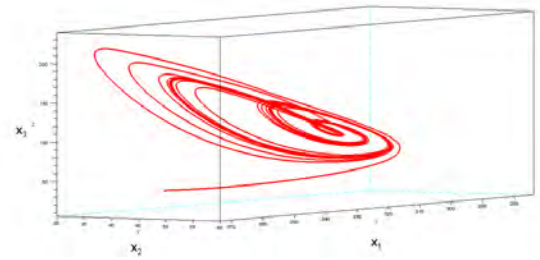

Figure 7. Well 2 state variables chaotic behaviour.

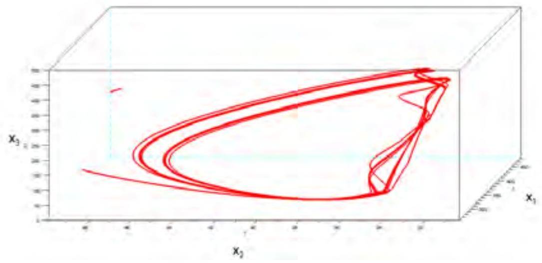

Figure 8. Well 1 state variables trajectory.

Further more, it is also important to know what is happening inside the three-phase separator. The main variable to be analyzed by the production engineer is the separator pressure, because it directly affects the production rate.

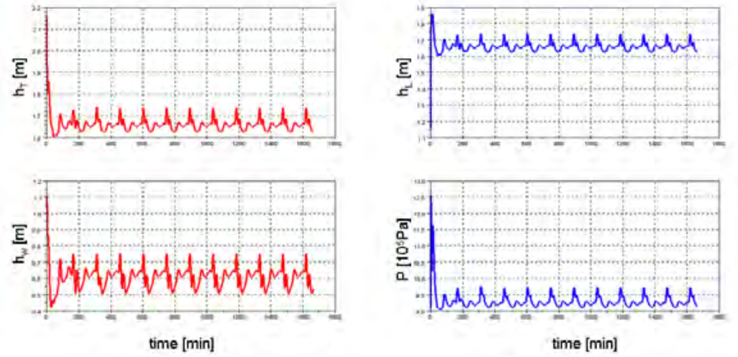

Figure 9. Three-Phase Separator's state variables with oscillatory production.

Depending on the oscillations' amplitude and frequency, the separator control system might not be able to maintain the average pressure at the original set-point and cause production losses in every well hydraulically connected to the same production header. Process problems and inefficiencies are also probable in such conditions.

Previous works (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. In this case, a stabilization through a control system might increase the production of the "unstable" well, stabilize the separator pressure and reduce its average pressure, thus increasing the production of every well connected to the same header.

4.2 Case 2 - Highly and Mildly Oscillatory wells

Although the main objective of this work is to analyze the influence of one oscillating well in the production system, sometimes there are more than one unstable well in the same production system and they might interact in different ways.

Such situation is presented in this section, where both Well 1 and Well 2 are predicted to oscillate at different frequencies. The simulation of coupled system results are presented in Fig. 10. The sate variables of Well 1 clearly indicate a Casing Heading behaviour, although a little distorted. In practical situations, this distortion is commonly attributed to measurements, complex two-phase behaviour and even non-predicted reservoir dynamics when in fact, in this case, it has absolutely nothing to do with any of these causes.

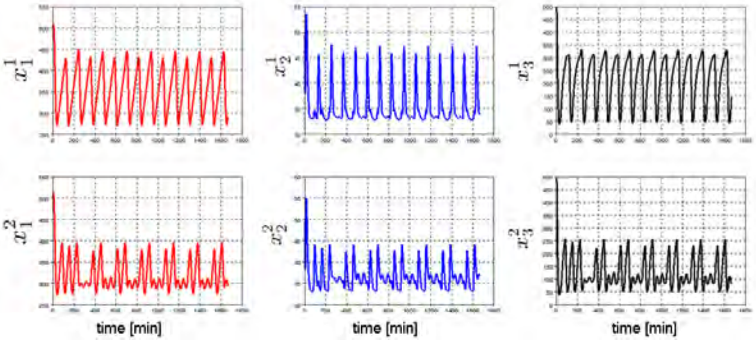

Figure 10. Well 1 and Well 2 state variables.

Even more interesting is the behaviour of Well 2. Even though the results presented in Fig. 10 are not operational parameters, they are qualitatively correlated. It can be observed that some cycles are missing in Well 2 and without the coupled model it is impossible to capture this dynamics. More than that, by observing only well variables, the engineer is not able to determine what is causing this behaviour, the non-linearity of the production system can generate non-intuitive phenomena. It is also important to note that this is not only a theoretical behaviour, but has also been observed in real production systems.

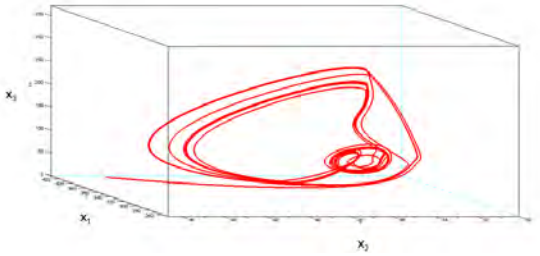

Figure 11. Well 2 state variables chaotic behaviour.

The chaotic behaviour of the state variables is presented in Fig. 11. If the simulations were performed for a longer time, more lines would appear in the plot because Well 2, although oscillating, is not periodic. The non-linearity causes the non-periodicity.

4.3 Case 3 - Intense hydraulic coupling and possible process shutdown

There are situations in which the dynamic coupling can be intense, depending on the system it could also present safety risks if not properly taken into account during the design phase. This section presents a production system with a non-oscillatory Well 2 with different dimensions ($L_a = 3500m$, $rgo = 0.01$) than Well 1 (as previously presented, it is unstable).

Figure 12 shows the separator's variables during this production. Initially, only the oscillatory behaviour of Well 1 is causing oscillations in the separator, for Well 2 is accumulating energy due to disturbances provoked by the dynamic coupling. Once the accumulated energy is freed by a production variation of Well 2, a great amount of gas and liquid enter the vessel modifying the steady state averages and causing a great pressure peak.

In this case, the pressure peaks can represent an increase in gas flaring, production losses due to back-pressure or even process shutdown. Moreover, the difficulty in level control can result in poor separation, carry-over, and also shutdown caused by low-low level in oil accumulation chamber. Besides that, production losses must be expected in such situations and, depending on the pressure peak amplitude, even safety risks can occur.

In order to prevent this hazardous dynamic coupling, one possible action would be to reduce the production choke valve opening set point. When it is about 10% of its maximum opening, the model estimates even an increase in total production, despite the higher pressure loss in the production choke. This can be explained by the fact that once separator pressure stabilization is achieved, in accordance with what is observed in practice, the average back pressure is lower.

5. CONCLUSIONS

This work employed simplified models, which can eventually be adjusted to match real complex production systems. The main objective was to show the influence of an oscillating well in the production system because of the hydraulic

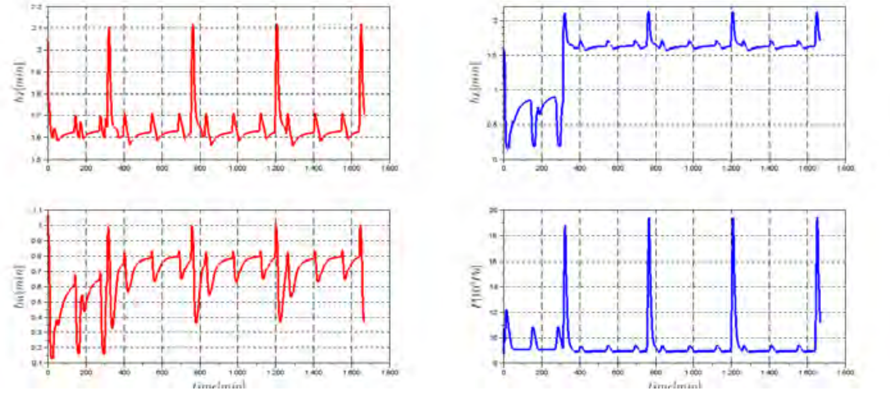

Figure 12. Three-Phase Separator's state variables with highly oscillatory wells.

coupling between different wells in the same production header.

Some situations (that were observed in real production systems) were modelled and simulated to show the most likely cause, which for these cases was the dynamic coupling. Without the analysis of the integrated production system, the engineer might be lead to erroneously conclude that the measurement is unreliable.

Other phenomena were attributed to reservoir non-modelled dynamics, complexity of two-phase flow or other explanation that would not help to solve the problem. Eventually, extremely high pressure peaks that even cause plant shutdowns occur in the production system and could be prevented.

It is evidenced that an integrated analysis is important to predict certain transient behaviours caused by hydraulic coupling. The integrated analysis is not only important during the plant operation but also during the design phase. Moreover, as the production wells were shown to be coupled, an optimum control system should be multi-variable taking into account state variables of different wells and even coupled with the separator control system, if possible. Obviously, a risk analysis must be performed.

Finally, without an integrated analysis, production losses could be hidden by the modification of the average separator parameters and could be interpreted as a reduction in the well's production capacity. The cross influence of unstable wells are also seen to be a cause of production losses and process inefficiencies.

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