Production Potential of Severe Slugging Control Systems

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Abstract: The application of riser top valve choking in severe slugging control has shown that feedback control stabilizes slug flow with a valve opening larger than manual choking, resulting in an increased oil production. However, the reason and ultimate potential for an active slug control system to increase oil production, as well as how to achieve this potential are still unclear. A systematic method based on the pressure bifurcation map of a riser system is proposed in this work to analyse the production and pressure loss relationship at the different operating points resulting from the various slug control strategies. It is shown that for a given unstable riser production system with known inlet and outlet boundary conditions, production loss or gain due to operation in stable or unstable operating conditions could be predicted by using a pressure dependent dimensionless variable known as production gain index (PGI). This gives a clear indication of the ultimate potential to increase oil production through feedback control. This analysis has been successfully applied to an industrial riser system modeled in the commercial multiphase flow simulator, OLGA. Production predicted by using the PGI agrees with actual simulated production. The analysis is based on the understanding that the closed-loop stable operating point must match the corresponding open loop unstable equilibrium point. This result is very significant in planning and implementing suitable control strategy for stabilizing unstable riser-pipeline production systems with the aim of achieving stability and ensuring increased productivity, especially for brown fields.

Keywords: Pressure, Feedback control, Closed loop, Open loop, Pipeline, Production system

1. INTRODUCTION

Severe slugging is an open loop unstable flow condition which occurs in offshore riser-pipeline production systems. Low well pressure, stratified flow regime in the pipeline and inclined pipeline geometry (upstream the riser) are the basic conditions necessary to initiate and sustain severe slugging. The resulting instability can affect the system adversely in many ways, (Hill and Wood, 1994).

The primary objective of a slug control system which is to eliminate slugging and ensure stable system operation has guided the common approach to slug control systems design and implementation. Among the solutions for slug control is riser top valve choking. Choking transforms the unstable flow in the riser to stable flow; however, it induces extra back pressure on the pipeline. Active feedback, feed forward and cascade control systems have been applied to dynamic choking for slug control (Henriot et al., 1999; Drengstig and Magndal, 2001; Jansen et al., 1996; Godhavn et al., 2005; Molyneux and Kinvig, 2000; Storkaas et al., 2001; Storkaas and Skogestad, 2004; Ogazi et al., 2010b, 2009b).

Although the implementation of a slug controller in the active choking solution has shown the potential to successfully eliminate severe slugging with some benefits, it can also adversely affect the overall production of the system if it is implemented inappropriately. As a result of this, the emphasis on the performance of slug control systems has recently shifted from just achieving a stable system condition to also maximizing production (Ogazi et al., 2010b).

However, the method for analysing the potential of a slug control system to maximize production and how this potential can be achieved have remained unclear. Most slug control systems are implemented without proper systematic assessment of its potential to maximize production in the system. In this work, a systematic method based on the pressure bifurcation map of the riser system is proposed to analyse the production and pressure loss relationship, and to reveal the potential to maximize production.

It is shown that for an unstable riser-pipeline system with known inlet and outlet boundary conditions, production loss or gain due to operation in stable or unstable operating conditions could be predicted using a pressure dependent dimensionless variable known as production gain index (PGI). The paper starts with the description of the pressure and production dependency analysis followed by production estimation using PGI analysis and a case study.

2. BACKGROUND

2.1 Severe Slugging

Severe slugging is a four stage cyclic unstable flow condition. These four stages are shown in Fig. 1, and briefly described below.

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2. Slug production
Controller
Liquid out
Liquid inlet
Gas inlet
1. Slug build up/formation
2. Slug production
3. Slug blow out
4. Fall back

Fig. 1. Severe slug cycle phenomenon illustrated

The process is initiated with the slug build up stage in which liquid cumulates at the riser base blocking the gas in the pipeline from flowing into the riser. The liquid blockage will expand both upstream and in the riser until liquid reaches the riser top. Then the slug production stage follows. In this stage, the liquid and gas interface upstream of the riser will move towards the riser until the gas penetrates into the riser to initiate the slug blow out stage. At the end of blow out stage, the residual liquid in the riser will fall back to riser base forming the fall back stage. Due to liquid fall back, the riser base will be blocked again by the liquid resulting in a cyclic phenomenon. This cyclic behaviour is highly undesired and requires control. Detailed description of the severe slug cycle can be found in the literature, Taitel (1986); Jansen et al. (1996).

2.2 Slug Control

Active control of the riser top valve has been widely adopted as a viable solution for eliminating severe slugging. Fig. 2 gives a schematic diagram of the offshore riser-pipeline system with an active feedback control structure. The basic concept of this approach is to manipulate the riser top valve opening \( u \) using a slug controller output whose control action is dependent on the deviation of a controlled variable from the set point.

Fig. 2. Schematic diagram of the industrial riser-pipeline system

However, the current industrial practice for implementing active control approach does not have a systematic method to analyse the production potential of severe slug control systems. Rigorous simulations and costly trial and error method are often applied. This is a current challenge which has necessitated the work presented in this paper.

3. PRESSURE AND PRODUCTION

The ultimate aim of stabilising severe slugging flow conditions is to achieve smooth and productive operation. Therefore, a slug control system should not only consider stability but also maximise oil production. For this purpose, it is necessary to analyse the effect of pressure loss associated with choking on the oil production. For simplicity, linear relations are assumed in the analysis below. Firstly, the pressure and production relationship of a linear well is to be discussed.

3.1 Linear Well Productivity

The relationship for determining oil production rate from a linear well can be derived generally from the Darcy’s law as given by Jamal et al. (2006).

\[
G_M = B(P_{res} - P_T)
\]

where \( G_M \) is the production rate, \( B \) the production index, \( P_{res} \) the reservoir pressure and \( P_T \) the flow line pressure, which can be defined as:

\[
P_T = P_{RB} + \Delta P_p(G_M)
\]

where \( P_{RB} \) is the riser base pressure and \( \Delta P_p(G_M) \) is the pressure loss along the pipeline, which depends on the production rate nonlinearly. For simplicity, this nonlinear function can be linearly approximated at a nominal flow rate, \( G_{M0} \), such that \( \Delta P_p(G_M) \approx K_pG_M + \Delta P_0 \), where both \( \Delta P_0 \) and \( K_p \) are constants. Therefore, (1) is equivalent to

\[
G_M = B_0(P_0 - P_{RB})
\]

(3)

where \( B_0 = \frac{B}{1 + K_p} \) and \( P_0 = P_{res} - \Delta P_0 \).

The relationship in (3) shows that \( G_M \propto (P_0 - P_{RB}) \). Therefore, an increase in the production rate can be achieved by reducing \( P_{RB} \), which depends on a number of system related factors including the downstream separator pressure, and pressure loss across the riser. Here, we will consider the \( P_{RB} \) dependency on opening of the choking valve including the pressure loss across the valve and riser. For a specific opening, the system can either be stable or unstable to be analysed correspondingly as follows.

For a stable operating condition, \( P_{RB} \) can be fairly constant, while for an unstable system, \( P_{RB} \) will oscillate significantly. For both conditions, the total production over a certain period, \( T \) is given as follows.

\[
Q_T = \int_0^T G_M dt = B_0(P_0 - \bar{P}_{RB})T = Q_0 - Q_p
\]

(4)

where \( \bar{P}_{RB} = \frac{1}{T} \int_0^T P_{RB} dt \) is the average pressure over \( T \), \( Q_0 = B_0P_0T \) is constant and \( Q_p = B_0\bar{P}_{RB}T \) is pressure dependent production loss.

3.2 Unstable Systems

For an unstable riser system, the average riser base pressure, \( \bar{P}_{RB} \) is calculated based on two prevalent pressure profiles that could be observed in an unstable riser-pipeline system. These are trapezoidal and irregular slug pressure profiles.
Trapezoidal Slug Pressure Profile

The trapezoidal slug pressure profile is typical and associated with the four stages of the severe slug cycle described in section 2.1. These four stages generate three pressure sections namely: the pressure build up section (section ab), the constant pressure section (section bc) and the pressure drop section (section cd), as shown in Fig. 3(a). The corresponding well-head flow profile can be derived from (3).

Irregular Slug Pressure Profile

An irregular slug pressure profile can take any shape, depending on the production conditions, the slug pressure profile could become irregular. For this trapezoidal shaped slug pressure profile, the average pressure \( \bar{P}_{RB} \) is derived as a function of the production period, \( T_p \) and the slug period, \( T_s \) and given as:

\[
\bar{P}_{RB} = P_{min} + \frac{1}{2} \left(1 + \frac{T_s}{T_p}\right)(P_{max} - P_{min})
\]

where \( P_{max} \) and \( P_{min} \) are the maximum and the minimum \( P_{RB} \) respectively. Note that (5) indicates that the more severe the slug flow, the longer the period \( T_p \), then the higher the average pressure, \( \bar{P}_{RB} \).

3.3 Stable Systems

For stable systems, the riser base pressure, \( P_{RB} \) is constant at steady-state, hence it is the same as \( P_{RB} \). However, for unstable flow conditions, such as severe slugging flows, steady-state is never reachable and the corresponding equilibrium is referred to as the unstable equilibrium. Assume that such an unstable system is represented by a differential equation as follows:

\[
\dot{x} = f(u, x), \quad \bar{P}_{RB} = g(x, u)
\]

where \( x \) is the state of the system, \( u \) is the opening of choking valve and \( P_{RB} \) is the riser base pressure. Then, the unstable equilibrium, \( x_e \) and the corresponding riser base pressure for a given valve opening, \( u_e \) is determined by the algebraic equations:

\[
f(x_e, u_e) = 0, \quad P_{RB_e} = g(x_e, u_e)
\]

If such an unstable system is stabilised by a feedback control, \( u = k(P_{RB}) \), then the steady-state of the stable closed-loop system, \( x_c, P_{RB_e} \) and \( u_c \) are determined as follows. \( 0 = f(x_c, u_c), \quad P_{RB_e} = g(x_c, u_c), \quad u_c = k(P_{RB_e}) \). Therefore, if \( u_c = u_e \), then \( x_c = x_e \) and \( P_{RB_e} = P_{RB_e} \), i.e. the steady-state of the stable closed-loop system must be equal to the unstable equilibrium condition in accordance with the same valve opening. The values of \( P_{RB_e} = P_{RB_e} \) at the unstable equilibrium point corresponding to a particular valve opening can be calculated using an accurate model of the system. However, it can also be obtained using the multiphase flow simulator such as OLGA.

For the riser system, \( u \) is the valve opening, which determines the operating point of the system. For a set of input values, say \( u = (u_1, u_2, ... u_n) \), the corresponding equilibrium values of \( x, x = (x_1, x_2, ... x_n) \) are determined by (8). These values can then be used for production analysis of active slug control.

4. PRODUCTION GAIN INDEX

For a riser system stabilised by a slug controller operating at a valve position, \( u_c \), the production gain when compared to an unstable slugging condition corresponding to an open-loop valve opening, \( u \), is \( Q_p(u) - Q_p(u_c) \). In order to describe the production potential of slug control systems, a dimensionless variable, the Production Gain Index (PGI) is introduced as the ratio of the production gain, \( Q_p(u) - Q_p(u_c) \) against \( Q_p(u_c) \) as follows.

\[
\xi(u, u_c) = \frac{Q_p(u) - Q_p(u_c)}{Q_p(u_c)} = \frac{P_{RB}(u)}{P_{RB_e}(u_c)} - 1
\]

The PGI as a function of \( u \) and \( u_c \) can be represented as contours in the \((u, u_c)\) plane. Amongst these contours is the zero PGI (ZPGI) contour defined as \( \xi(u, u_c) = 0 \), which divides the \((u, u_c)\) plane into two areas: the positive PGI (PPGI) area which is located above the ZPGI line and the negative PGI (NPGL) area which is located below the ZPGI line. This is shown in Fig. 6 for a particular case to be discussed in section 5.

According to the definition of the PGI in (10), the PPGI area corresponds to production gain operating points, i.e.
for any point \((u, u_c)\) in this area, if a slug controller can stabilise the system at the valve opening, \(u_c\), then the corresponding production will be larger than the one obtained when the valve opening is fixed at \(u\) without any control.

Similarly, the NPGI area indicates production loss operating conditions, \(i.e\). for a point \((u, u_c)\) in this area, if a slug control stables the system with valve opening \(u_c\), the resulting production will be less than the one corresponding to the valve opening fixed at \(u\) without control.

5. CASE STUDY

To illustrate the application of the PGI analysis method to reveal the production potential of a riser-pipeline system, we will use an industrial riser system, which had been described by Ogazi et al. (2009a). The open loop stability of this system can be analysed using the hopf bifurcation map.

5.1 Hopf Bifurcation Map

The Hopf bifurcation occurs in a dynamic system, when the system losses stability due to changes in an independent variable (Thompson and Stewart, 1986). For the riser-pipeline system, Hopf bifurcation can occur if a change of the valve opening causes the system to become unstable at an operating point. The phenomenon can be depicted by the so called bifurcation map. The \(P_{RB}\) Hopf bifurcation map of the industrial riser system is shown in solid lines in Fig. 5. The bifurcation map indicates that the maximum valve opening corresponding to a stable system is \(u_{mos} = 12\%\). For \(u > u_{mos}\), the system becomes unstable, and oscillates between the maximum and minimum pressure values. Therefore, \(u_{mos}\) is known as the bifurcation point. We will calculate the \(P_{RB}(u)\) and \(P_{RBc}(u_c)\) of the system for \(12\% < u, u_c \leq 100\%\).

5.2 Industrial Riser System

In this section, we will calculate the \(P_{RB}\) and \(P_{RBc}\) for the industrial riser system for each of the open loop unstable operating points.

Calculating \(P_{RB}\) To calculate the \(P_{RB}\) for the industrial riser system for \(12\% < u \leq 100\%\), the system is simulated using the OLGA model to obtain the \(P_{RB}\) profile. The \(P_{RB}\) profile obtained at four different valve openings are shown in Fig. 4.

\[\text{Fig. 4. Riser base pressure profile}\]

From Fig. 4, we observe that these \(P_{RB}\) profiles are almost irregular in shape. Thus, we can calculate the \(P_{RB}\) using equation (6), with \(N = T_s\); where \(T_s\) is the slug period. The \(P_{RB}\) is calculated for each operating point. The values of \(P_{RB}\) obtained for each operating point are plotted in the solid line with square marks in the bifurcation map shown in Fig. 5.

Calculating the \(P_{RBc}\) To calculate the \(P_{RBc}\), we can use the OLGA model. To use the OLGA model, first the steady state option must be turned on in the case definition/options property bar. Also the initial valve opening should be specified for each operating point. The \(P_{RBc}\) is obtained in the pressure trends as the initial steady state value at \(t=0\).

The \(P_{RBc}\) obtained using the OLGA model are plotted a dashed line as shown in Fig. 5.
For any point on the ZPGI line defined by \((u, u_c)\), a PPGI will be obtained with reference to the \(u_c\) for all open loop operating points less than the corresponding \(u\). Thus, the production obtained at \(u_c\) will be higher than that obtained for all open loop operating points less than the corresponding \(u\). For example, for the ZPGI point defined by \((49\%, 20\%)\), we can predict that the production obtained with a slug controller at \(u_c = 20\%\) will be higher than that obtained for all open loop operating points \(u < 49\%\).

However, for any point on the ZPGI line defined by \((u, u_c)\), a NPGI will be obtained with reference to the \(u_c\) for all open loop operating points greater than the corresponding \(u\). For example, for the ZPGI point defined by \((49\%, 20\%)\), we can predict that the production obtained with a slug controller at \(u_c = 20\%\) will be less than that obtained for all open loop operating points \(u > 49\%).

From these analyses, we can deduce that for any point on the ZPGI line defined by \((u, u_c)\), the production obtained at any operating point greater than the \(u_c\) will be higher than that obtained for all open loop operating points less than or equal to the corresponding \(u\).

These analyses provide a very useful insight into the production potential of this industrial riser system. It also shows that the extent to which a feedback controller can assure increased production depends on the maximum closed loop operating point the feedback controller can achieve. Thus, the decision on whether to implement a feedback controller or not in order to stabilise the system as well as maximise production can easily be made without rigorously simulations or costly trial and error method.

### 5.4 Simulated Production

In this section, we will analyse the actual production obtained from a 24 hour simulation of the industrial riser system under closed loop and open loop operating condition and compare it with the predictions of the PGI analysis. Open loop simulation is performed for all the operating points of \(15\% \leq u \leq 100\%\) and the accumulated production for a 24 hour period is recorded. Unlike the open loop simulation, the closed loop simulation will require a stabilising controller. To meet this requirement, two slug controllers namely:

1. relay tuned slug controller
2. robust PID slug controller

are implemented and analysed.

**Implementation of the Relay Tuned Slug Controller**

The implemented relay tuned slug controller \((K_1)\) is a PI controller which has been reported in a previous work, Ogazi et al. (2010a). The relay is designed using process parameters obtained from the system response which is determined by the shape factor analysis. The controller transfer function is given in (11).

\[
K_1 = \frac{-31.86s - 0.18}{177s} \tag{11}
\]

This controller when implemented on the industrial riser system can stabilise the system to a maximum closed loop operating point of \(u_c = 33.13\%\). The open and closed loop simulated productions are shown in Fig. 7.

**Implementation of the Robust PID Slug Controller**

The implemented robust PID slug controller \((K_2)\) is also a slug controller which has been reported in a previous work, Ogazi et al. (2010b). The controller is designed based on a number of robust stability and performance criteria. The controller transfer function is given in 12.

\[
K_2 = \frac{-16s^2 - 3200s - 4}{800s} \tag{12}
\]

This controller when implemented on the industrial riser system can stabilise the system to a maximum closed loop operating point of \(u_c = 57.6\%\). The open and closed loop simulated productions are shown in Fig. 8.

The comparison of these simulated productions with the PGI predictions is presented in the next section.

### 5.5 Simulated Production Comparison

From the simulated production obtained using the two slug controllers, we observe that the production at \(u_c = 20\%\) is 3\% and 0.17\% higher than the open loop production at \(u = 30\%\) and \(u = 40\%\) respectively. However, the open loop production at \(u = 50\%\) is 2.29\% higher than the closed loop production at \(u_c = 20\%).
Comparing these productions to the PGI predictions in section 5.3, which predicted that closed loop production at $u_c = 20\%$ will be higher than the open loop production at any operating point of $u < 49\%$, and that closed loop production at $u_c = 20\%$ will be less than the open loop production at any operating point of $u > 49\%$, we can observe that the simulated production at $u_c = 20\%$ agrees with the PGI predictions. When similar comparison is done for the closed loop production at $u = 15\%$, the simulated production also agrees with the prediction of the PGI analysis.

Also, we can observe from the simulated production that the closed loop production at $u_c \geq 30\%$ is higher than the open loop production for all the open loop operating points, $15\% \leq u \leq 100\%$. Thus, the production of the relay tuned slug controller at $u_c = 33.13\%$ is higher than the production at all the open loop operating points, $15\% \leq u \leq 100\%$. This is also the case for the robust PID controller at $u_c = 57.6\%$. This agrees with the PGI prediction defined by the point (100%, 27%) in Figure 6.

Thus, the above analysis confirms that the production potentials of the riser-pipeline system predicted by the PGI analysis agrees with all the actual simulated production results. Hence, at this point, we can say that with proper PGI analysis of a riser-pipeline system, the production potential of the system at any operating point can be predicted.

6. CONCLUSION

In conclusion, the PGI analysis has been shown as an accurate systematic method for predicting the production potential of the riser system. These results are very significant when planning control strategy for stability and production, especially for brown fields.

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