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Learning control for riser-slug elimination and production-rate optimization for an offshore oil and gas production process [★]

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Abstract: Slugging flow in the offshore oil & gas production attracts lot of attention due to its limitation of production rate, periodic overload on processing facilities, and even direct cause of emergency shutdown. This work aims at two correlated objectives: (i) Preventing slugging flow; and meanwhile, (ii) maximizing the production rate at the riser of an offshore production platform, by manipulating a topside choke valve through a learning switching model-free PID controller. The results show good steady-state performance, though a long settling time due to the unknown reference for no slugging flow.

Keywords: Offshore, oil & gas, anti-slug, production-rate optimization, learning control.

1. INTRODUCTION

The oil and gas industry has spent a lot of time and effort in optimizing the production process. One area of interest is the reduction of severe slug in pipeline and riser systems. Some operating conditions lead to undesired flow regimes, since they cause varying flow rates and pressures in the system. Both the flow and pressures can either be constant or follow sinusoidal periodic cycles. When the flow and pressures are varying in cycles, the production rate will be significantly reduced with regards to the safety issues and sometimes the fluctuation may lead to system shut down. There exist several consequences of having these oscillations: liquid overflow and high pressure in the separators, overload on gas compressors, fatigue caused by repeating impact, high frictional pressure drop, low production, and production stop, (Hill and Wood (1994)). The slug flow is the flow pattern creating the biggest oscillations.

There are several different types of slugging flow, and riser-induced slug is a severe slug type. Fig. 1 illustrates the periodic slugging behavior of a vertical riser pipeline in 4 steps: (1) Liquid accumulates in the bottom of the riser. (2) When more gas and liquid enters the system, the pressure increases and the riser fills up with liquid. (3) After the blocked gas has built up, the pressure will be large enough to blow the liquid out of the riser. (4) After the blow-out, the liquid starts to build up in the bottom of the riser and the cycle repeats.

Being able to avoid the slug flow in the pipelines is of big economic interest. For this reason it is important to be able to predict the flow regime before the process causes problems. Traditionally flow maps are designed for each unique system from empirical data, see Hewitt and

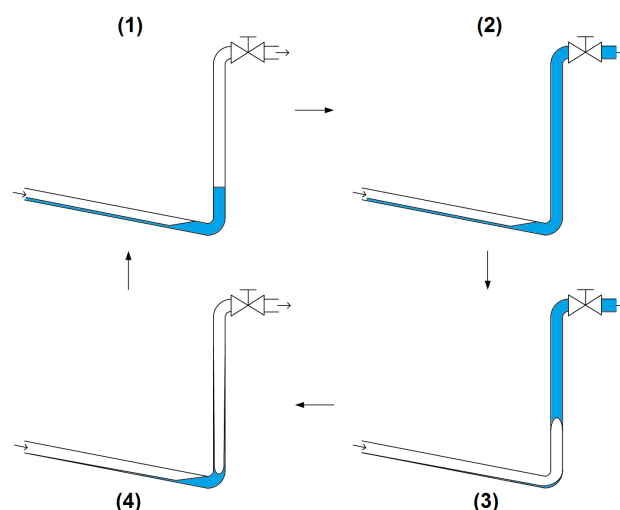


Fig. 1. Illustration of the cyclic behavior in a riser pipeline when slug occurs. A controllable choke valve is located at the top of the riser.

Roberts (1969) and Li et al. (2013). They indicate which flow pattern is represented in steady-state. It is noted that the flow maps are open-loop maps, with no control feedback loops being represented.

Some riser slug models have been proposed by Jahanshahi and Skogestad (2011), where a 4 state model has been developed, and Meglio et al. (2009), where a 3 state model has been developed. Earlier studies of a small-scale setup has been performed by Baardsen (2003). Some model-based control strategies of slugging is mentioned in Meglio et al. (2012). Furthermore Ogazi et al. (2010) and Isaac et al. (2011) have proven that control of the flow and slugging can increase production.

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Control techniques of eliminating the slugging has been studied by Meglio et al. (2012), Jahanshahi et al. (2013), and Pagano et al. (2009). These studies concern nonlinear model-based methods and their comparison with simple PID controllers. This study will focus on a simple model-free controller, using an advanced learning algorithm.

The work described in this paper is based on a constructed lab setup developed in Biloft et al. (2013), who also studied the re-creation of slug from experiments on this testing facility. The small-scaled testing facility is described in section 2. The rest of this paper will describe the development of controllers and the implementation at the lab facility, as well as analysis based on these results.

The rest of the paper is organized in the following order: In section 2 a review of the lab-sized setup developed by Biloft et al. (2013) is described. Section 3 explains the development and implementation of two controllers: (i) Learning controller with unknown reference for production rate subject to no slugging flow in 3.1, and (ii) Controller with known reference in section 3.2. A conclusion and future work is described in section 4.

2. LAB TESTING FACILITY

Biloft et al. (2013) studied the development of an economic lab-sized setup built at Aalborg University, Denmark. The main objective of this facility is to emulate different flow patterns often happening at the offshore oil and gas production platforms.

The construction consists of horizontal and vertical pipes which simulate a real pipeline/riser system. Water is transported through the pipeline and riser to the choke valve and lead to the separator and back to the water reservoir to close the loop. Air is injected at the start of the pipeline, transported through the system and let out after the choke valve. The angle of the horizontal pipe can be adjusted from 0° to 20° , and the placement of the air injection can be moved from start of the pipeline to the bottom of the riser to facilitate different scenarios (e.g. only riser).

A diagram of the setup can be seen in fig. 2. **DPT** is the difference pressure over the pump, **PT1** is the riser bottom (lowpoint) pressure transmitter, **PT2** is the topside pressure transmitter, **PT3** is the separator pressure which here is the atmospheric pressure, **F1** and **F3** are the injection mass flow transmitters, and **FT2** is the outflow mass flow measurement. The topside choke valve is a ball choke valve.

2.1 Running conditions

For this study a constant water and air flow of respectively 0.1 kg/s and $1.72 \times 10^{-4} \text{ kg/s}$ is injected into the system. The topside choke valve is considered fully open at 60% because the separator is an open tank unable to pressurize, hence the choke valve will create the back pressure required.

Both the air and water injection values are defined by the designer to ensure a small mass velocity, thus riser-induced slug is easily created (Taitel (1986)).

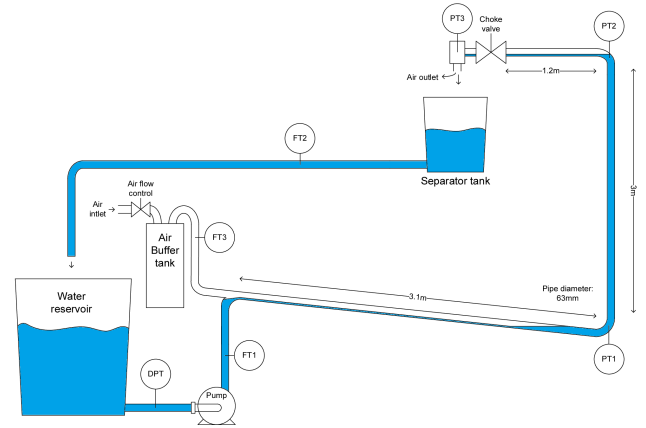


Fig. 2. Overview of the constructed lab-setup. Length of horizontal pipeline is 3.1 m, height of riser is 3 m, and length from riser to choke valve is 1.2 m. All pipe diameters are 6.3 cm (Biloft et al. (2013))

2.2 Bifurcation map

The slug could potentially be eliminated with the controlled choke valve, which, if controlled properly, would induce back pressure in the choke valve. Measuring the minimum and maximum low point pressure, for several different opening references will result in a map of the steady state performance of the system. This map is called the Bifurcation map. Hopf Bifurcation is defined as a dynamic system which loses its stability as a pair of complex conjugate eigenvalues of the linearized system cross the imaginary axis of the complex plane. From linear mathematical theory it can be noted as:

$$\text{Re}(\lambda_{1,2}(J(x_0, u_0))) \geq 0 \text{ for } z > a_{bp} \quad (1)$$

$$\text{Re}(\lambda_{1,2}(J(x_0, u_0))) < 0 \text{ for } z \leq a_{bp} \quad (2)$$

$\lambda_{1,2}(J(x_0, u_0))$ are the eigenvalues of the Jacobian linearization, linearized around the states for two dominant conjugated poles, x_0 , and the inputs, u_0 . z is the choke valve opening and a subset of the inputs, and a_{bp} is the bifurcation point.

Figure 3 shows the pole-zero map using the Jacobian linearization of a nonlinear model by changing the choke valve opening, u_0 . The model is explained in detail in Biloft et al. (2013). It is based on the three mass balance equations (3), (4), and (5), where ϵ is the ratio of gas in the pipeline, and ω is the mass flow. From the figure it is observed that there are three states, but the linearization shows that two conjugated poles are dominant in the system. These poles are crossing the imaginary axis as the choke valve opening increases, thus the Hopf Bifurcation is occurring.

$$\dot{m}_{g,eb}(t) = (1 - \epsilon)\omega_{g,in}(t) - \omega_g(t) \quad (3)$$

$$\dot{m}_{g,r}(t) = \epsilon \cdot \omega_{g,in}(t) + \omega_g(t) - \omega_{g,out}(t) \quad (4)$$

$$\dot{m}_{l,r}(t) = \omega_{l,in}(t) - \omega_{l,out}(t) \quad (5)$$

The bifurcation map for the running conditions has been carried out by Biloft et al. (2013) and can be seen in fig. 4. It is observed that there are two bifurcation maps: One

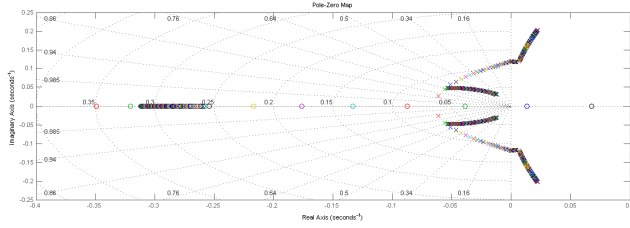


Fig. 3. The pole-zero map of the linearized model. The figure is showing the two dominant poles as well as one zero. The Hopf bifurcation behavior occurs when the two conjugated poles are crossing the imaginary axis.

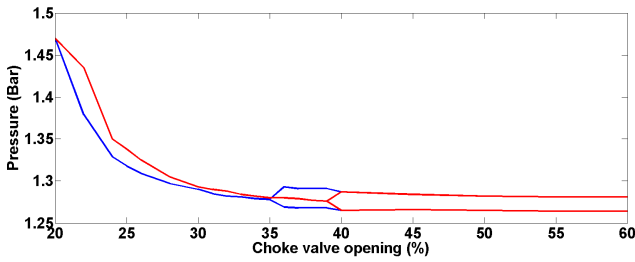


Fig. 4. Bifurcation map. Blue line is for decreasing choke valve opening and red line is for increasing. At 35% the slugging behavior will start fading and at 39% the phenomenon returns (Biltoft et al. (2013)).

where the choke valve opening, z , is decreasing (blue line), and one where the choke valve opening is increasing (red line). It is clear that there are two bifurcation points, 35% and 39% depending on how the choke valve is changing. This feature is being utilized in section 3. At the bifurcation points the graph divides into two separate lines, indicating a steady pressure changing to an oscillating pressure where the top graph is the maximum pressure and the low graph is the minimum pressure of one slug cycle.

Often the lowpoint pressure of the riser pipeline is not measured on offshore platforms, however a topside pressure transmitter is often available. This transmitter can be used to estimate the the lowpoint pressure (Helgesen (2010), Sivertsen and Skogestad (2005)).

3. CONTROL STRATEGY AND DEVELOPMENT

A SISO controller is considered, where the lowpoint pressure is the output measurement. The elimination of the slug is being carried out by manipulating the choke valve, however the production will decrease as the choke valve decreases. This can be proven by investigating the model constructed by Meglio et al. (2009) with the adjustments made in Meglio et al. (2012), where the nonlinear valve equation is stated as in equation (6).

$$\omega_{out} = C(\rho(P_{top} - P_s))^{1/n} z \quad (6)$$

ω_{out} is the flow after the topside choke valve into the separator, ρ is the density, P_s is the pressure in the separator, P_{top} is the pressure at the top of the riser just before the choke valve, z is the choke valve opening percentage, and n is 1 for laminar flow and 2 for turbulent

flow. n is a tuning parameter ranging from 1 to 2, as this value in most cases attains the value of 2, n is chosen to 2 to reduce the amount of tuning parameters.

It is clear that any closing of the choke valve will decrease the outflow into the separator, ω_{out} , subject to keeping other variables constant. Hence the objective of the controller is to eliminate the slugging flow, while having the choke valve opening as high as possible.

3.1 Learning controller with unknown reference

The bifurcation behavior is being used as a main feature for the controller development. However if the tests for the bifurcation maps are not carried out, the bifurcation points are unknown. Achieving the right reference of the lowpoint pressure subject to no slugging flow is the main challenge of the controller design, since the bifurcation points give the choke valve opening references for the controller. On many pipeline-riser systems the bifurcation data is not available, hence to make a controller which can work on any pipeline-riser system, some type of learning controller is needed. In the following, a learning switching control solution is proposed. This method does not require any pre-knowledge of the concerned platform system.

The developed controller aims to achieve the following two objectives: Eliminating the slug, while optimizing the production rate. A sliding window of the lowpass filtered absolute changing rate value of the lowpoint pressure over time, $\left| \frac{d\bar{P}}{dt} \right|$, is used to detect whether the slugging occurs or not, as seen in equation (7). The low-pass filter is designed with the cutoff frequency above the largest slugging frequency.

$$\left| \frac{d\bar{P}}{dt} \right| > \text{slug threshold} \quad (7)$$

When $\left| \frac{d\bar{P}}{dt} \right|$ is big, the changing rate of the pressure is high, thus the flow is slugging.

Another way to determine the slug is by taking the difference pressure from top to bottom. The pressure difference is mainly caused by the weight of the liquid in the riser. When the flow is slugging the pressure difference will be smaller when the gas is accumulating at the bottom of the riser, and bigger in the blowout phase where the riser is filled with gas. Equation (8) shows this relationship. Other mathematical detection methods have been studied in Mokhatab (2010).

$$\text{Top slug threshold} > P_{top} - P_{bottom} > \text{Low slug threshold} \quad (8)$$

If slug occurs controller 1 is activated, and if slug does not occur controller 2 is activated.

- (1) The objective of controller 1 is to eliminate the slug when slugging behavior is detected. The controller is slowly choking the valve using a PID controller until the elimination of the slug is carried out. At the elimination point, the lowpoint pressure is being saved, for a new reference when the controller is activated.

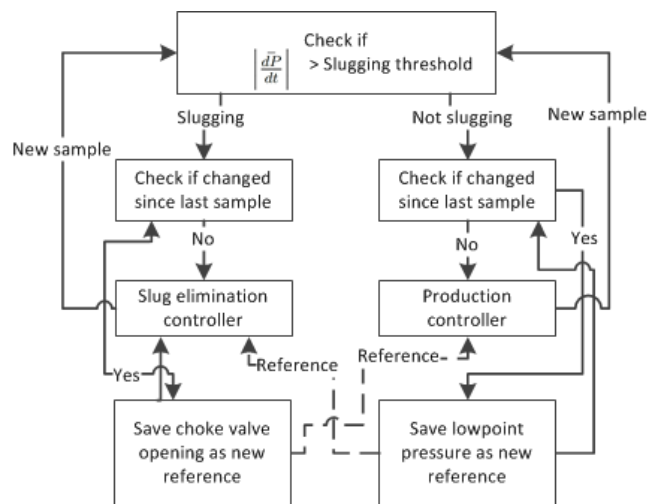


Fig. 5. Illustration of a block diagram of the control algorithm. The solid lines indicate the procedure of the algorithm, and the striped lines indicate that the algorithm sets new references.

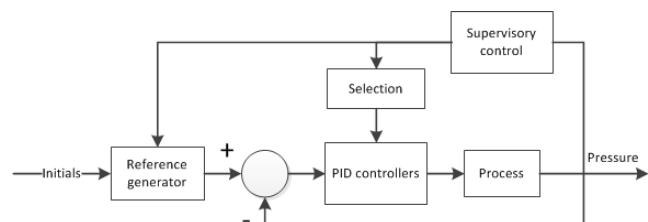


Fig. 6. Illustration of the control scheme. The supervisory control is based on the slug detection, and is finding the references. The selection part is switching between the PID controllers.

- (2) The second controller is activated when the slug is eliminated. Slowly opening the choke valve using a PID controller will keep the steady flow behavior for a certain period, until the slugging reoccurs. At the point where the flow is changing the opening percentage of the topside choke valve is being saved as a new reference when the controller is activated.

The controller algorithm is shown in figure 5. The solid lines indicate the procedure of the algorithm, and the striped lines indicate that the algorithm sets new references. The slug detection calculation is determining which controller is being applied, and the changing of flow patterns determines when the the references are being saved.

Slug detection (see equation (7)) is part of the supervisory control, which also finds the references based on the learning procedure. The slug detection is combined with a selection block which switches between the two PID controllers. The implemented control scheme is shown in figure 6. The figure shows that the lowpoint pressure is used as the only output measurement used for the controller design, where the supervisory control evaluates the pressure changing rate, hence giving the controller reference and helps the selection block decide which PID controller values to use. Thus there are two independent PID controllers, one when the supervisory control requires the valve to open, and one for closing.

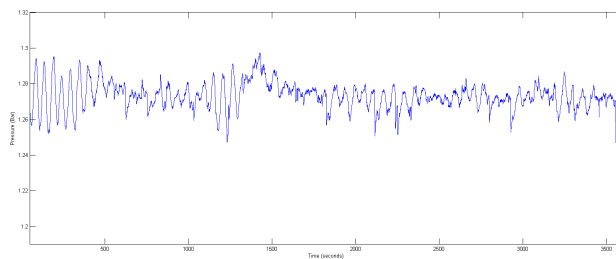


Fig. 7. The graph shows the bottom pressure under the influence of the controller. It is observed that the pressure initially oscillates before stabilizing, then oscillating, and finally stabilizing at steady-state.

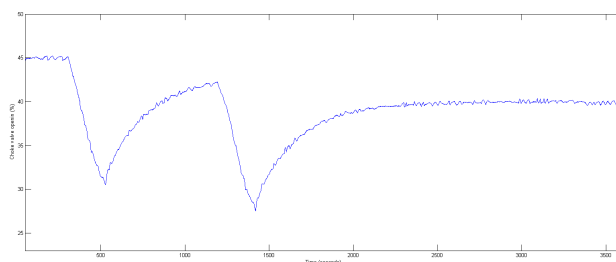


Fig. 8. The graph shows the input to the controller, which is the choke valve opening.. It is observed that the pressure initially is oscillating, before stabilizing, then oscillating, and finally stabilizing at steady-state.

The implementation of the controller on the lab-sized setup can be observed in figure 7. The figure illustrates the lowpoint pressure of the riser. The controller is being activated after 200 seconds, to show the oscillation before the controller is added. At first the system is slugging which is being eliminated by choking the choke valve, then the choke valve is slowly opening until the slugging reoccurs. When the slugging reoccurs the first controller is activated again to eliminate the slug, and then the second controller knows the opening reference, thus the system stabilizes. Figure 8 shows the choke valve opening while the controller is enabled. Here it is observed that the controller learns maximum allowed opening reference and stabilizes the system.

It is observed that the pressure is varying when the slug is not occurring, this is caused by measurement noise.

At this point it is hard to determine the controller's performance, because the injections are constant. It is however observed that the controller successfully eliminates the slugging flow, and stabilizes the bottom pressure. Another test is carried out with the same controller, but where the water pump is given a constant voltage input to emulate the pump's constant effort. By measuring the outflow and applying this change, the performance can be determined by comparing the controller with the fully open choke valve (no controller applied). Figure 9 is showing the lowpoint pressure of the new test using the same controller, and figure 10 is showing the corresponding opening of the choke valve.

It is observed that the controller is stabilizing the pressure, as shown on the previous test. Observing the outflow transmitter (which is emulating the production rate) can

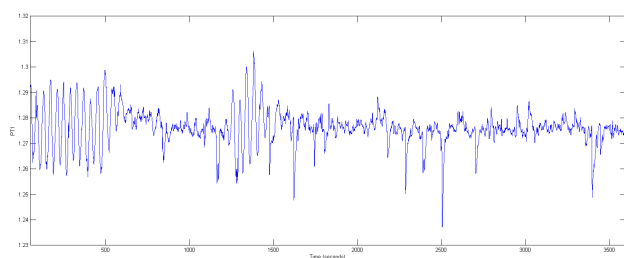


Fig. 9. The graph shows the bottom pressure under the influence of the controller, and with constant pump effort. It is observed that the pressure initially is oscillating, before stabilizing, then oscillating, and finally stabilizing at steady-state.

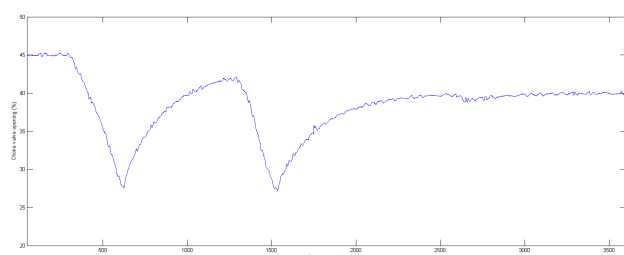


Fig. 10. The graph shows the input to the controller, the choke valve opening, and with constant pump effort. It is observed that the pressure initially is oscillating, before stabilizing, then oscillating, and finally stabilizing at steady-state.

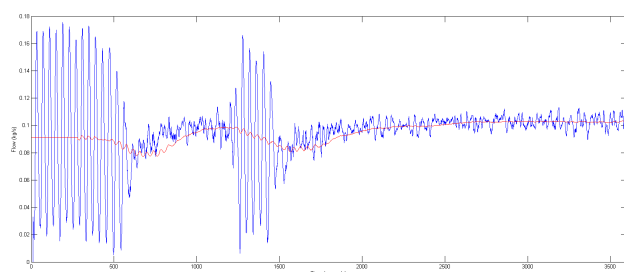


Fig. 11. The graph shows the mass flow out of the separator, under influence of the controller, and with constant pump effort. The blue line is the measured mass flow and the red line is the average over a short period of time.

evaluate the controller's performance. The water mass outflow, measured in kg/s, is seen on figure 11.

The mass flow rate out of the separator is giving a production increase of **7.8 %** at steady state. Besides, this controller will work on any setup with any constant or slow-varying running conditions, since the learning process will adjust to any running conditions. The transient response however is very slow; the settling time is approximately 2500 seconds. It is observed that one slug cycle is lasts 42 seconds on average, hence the settling time lasts 60 cycles. This is a great motivation to speed up the controller performance while keeping the good steady-state results.

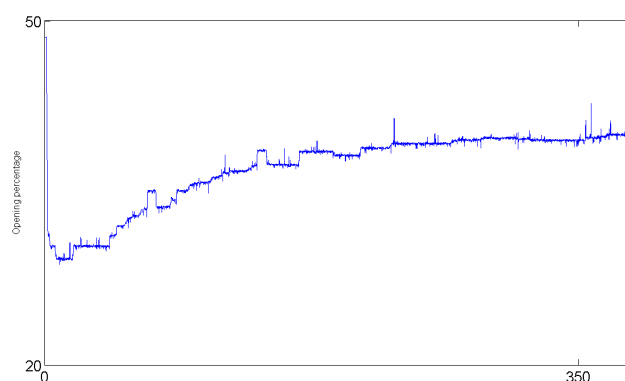


Fig. 12. The graph is showing the the opening percentage of the choke valve under influence of the controller where the references are already known.

3.2 Controller with known reference

Now it is assumed that the bifurcation map is known for the given running conditions, thus the controller does not need to be self-learning, because the reference point now is known. Figure 4 illustrates the bifurcation map of the lab scaled setup with the running conditions mentioned in section 2.1. This is the information which is being used for the new controller design.

The controller scheme will be as mentioned in section 3.1, however since no sliding window is needed to detect whether the slug flow occurs or not, the reaction of the controller is faster; hence the controller can be much more aggressive. The bottom pressure is still used as an output, and the choke valve opening as an input. Now the supervisory controller's main purpose is to calculate the pressure changing rate rather than detect the slug. The new switching controller is designed the following way:

- (1) The system is slugging and the choke valve is closing fast to the elimination set-point, 35%, using an aggressive PID controller. There are some restrictions on how fast the choke valve can close, but compared to the settling time this restriction time is very small, thus not affecting the transient performance.
- (2) Now the slugging is eliminated and a new controller is being applied to open the choke valve to the highest opening, where slugging is not occurring, 39%. The choke valve is required to open in a slow manner, since the bifurcation map found is created by slowly changing the opening of the choke valve, and faster changes will recreate the slug. Hence the PID controller is not aggressive.

Figure 12 shows the opening percentage of the choke valve using the new controller with the known reference on the same configuration as in section 2.1. It is observed that the first PID controller is only applied in the initial 15 seconds, before the controller switches to the second PID controller, which is slowly increasing the valve opening to the optimal opening percentage. Figure 13 shows the corresponding pressure at the bottom of riser under the same test. Here it is observed that the controller is eliminating the slug after one cycle.

From these tests it is observed that the slug is eliminated after one slug cycle and the settling time is reduced to 300

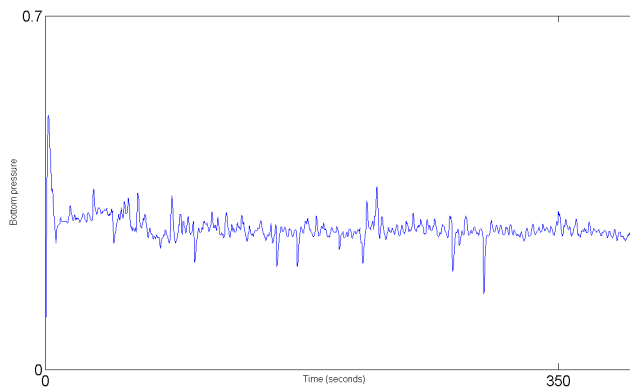


Fig. 13. The graph is showing the the pressure at the bottom of the riser under influence of the controller where the references are already known. It is observed that initially one slug cycle occurs before the slug is being eliminated.

seconds. Hence the main objective of reducing the settling time is being achieved.

4. CONCLUSION

The study described in this paper has examined the tests obtained from a testing lab facility, the construction of a learning controller scheme, the implementation of the controller, and the evaluation of the controller's performance from the implemented tests. The paper investigates intelligent manipulation of a topside choke valve, by the riser lowpoint pressure measurement. This measurement is not always available, but can be estimated, if a topside pressure transmitter is available.

The tests show bifurcation behavior which is being used as a key feature in the controller design. The controller is designed with a supervisory controller which is based on the slug determination. The implemented controller shows an 7.8 % production increase at steady-state, however the settling time is long. The learning controller is compared to a controller with no learning algorithm, but with the knowledge of which reference to aim for. This improves the transient performance by reducing the settling time from 2500 to 300 seconds but with the same steady-state production increase.

Because of these results it can be concluded that a proper learning controller of a topside choke valve can increase the production rate significantly in a small-scaled testing facility. With some pre-knowledge of the bifurcation points, it is further possible to reduce the settling time. The main advantage of the learning controller algorithm over existing choke valve controllers, is the ability of the controller to work on all pipeline-riser platforms with any dimensions and running conditions. However, before it is possible to guarantee the same performance on a real offshore platform, some simulation tests will be required to compare the experimental test results with the simulations of a real-sized platform.

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