European Symposium on Computer Aided Process Engineering – 15
L. Puigjaner and A. Espuña (Editors)


# Anti-slug control experiments on a small-scale two-phase loop

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## Abstract

Anti-slug control applied to two-phase flow provides a very challenging and important application for feedback control. It is important because it allows for operation that would otherwise be impossible, and challenging because of the presence of both RHP-poles and RHP-zeros.

To conduct experiments on pipeline-riser anti-slug control, a small-scale slug-loop has been build. The loop has been modeled and analyzed using a simplified model by Storkaas. The results from this analysis and experimental results using a PI-controller is presented in this paper.

**Keywords:** feedback control, riser slugging, controllability analysis

## 1. Introduction

Some of the problems in the offshore oil industry that have received increasingly interest in the last years are related to multiphase flow. In multiphase flow different flow regimes can develop, depending on parameters such as flow rates, fluid properties and pipeline geometry.

Slug flow is a flow regime which can cause a lot of problems for the production facilities. The slug flow is characterized by alternating bulks of gas and oil, and can be further divided into hydrodynamic and terrain induced slugging. Hydrodynamic slugs are caused by velocity differences between the phases and occur in near horizontal pipelines. These slugs are usually short and appear frequently. Terrain induced flow however, can contain a lot of liquid and therefore induce large pressure variations in the system. This flow is induced by low points in the pipeline geometry.

When the low-point is realized by a downsloping pipe terminating in a riser, we get what is known as riser slugging. Because of the large and abrupt fluctuations in pipe pressure and gas and liquid flow rates at the outlet, these slugs cause huge problems for the processing equipment. Unwanted variations in the separator level give rise to poor separation and possible overfilling. The pressure fluctuations wear and tear on the equipment and can sometimes result in unplanned process shutdowns.

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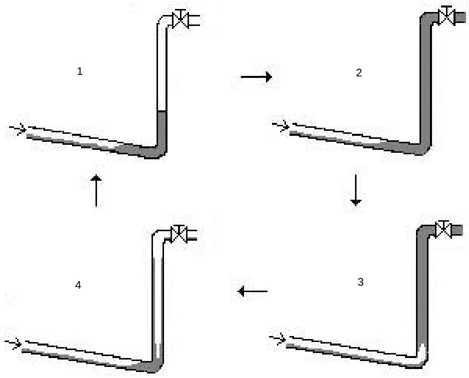


*Figure 1. Illustration of the cyclic behavior (slug flow) in pipeline-riser systems*

The behavior of pipeline-riser slug flow is illustrated in Figure 1. Liquid accumulates in the lowpoint of the riser, blocking the gas (1). As more gas and liquid enters the system, the pressure will increase and the riser will be filled with liquid (2). After a while the amount of gas that is blocked will be large enough to blow the liquid out of the riser (3). After the blow-out, a new liquid slug will start to form in the lowpoint (4).

Several solutions for eliminating or reducing these problems have been proposed (Sarica and Tengesdal, 2000), but they usually come at a price. Choking the valve at the top of the riser is one example of this. The slugging will disappear, but the increased pressure drop over the valve will lead to a lower production rate.

Stabilizing the flow using active control has been proposed earlier and also tested out both on experimental rigs (Hedne and Linga, 1990) and on offshore installations (Havre et al., 2000) and (Courbot, 1996). It has been proved that it is possibly to stabilize the flow at a pressure drop that would lead to slug flow if left uncontrolled. However, there is still a lot that can be done on deciding which measurements and control configuration gives the best results. Some measurements, like the inlet pressure, can even be hard to implement and maintain.

A small-scale loop (the Miniloop) was build in order to test out and analyze different control strategies in a cheap and easy way. The loop is very simple with a flow consisting of only two phases, air and water. We still get the same slugging phenomenon as expirienced offshore, with pressure fluctuations and varying flow rates. This makes it possible to screen different ideas before testing them on larger and more expensive experimental rigs and a lot of money can be saved.

## 2. Experimental setup

To test different control configurations, a small-scale two-phase flow loop with a pipeline-riser arrangement was build. The flow consists of water and air, which are mixed at the inlet of the system. Both the pipeline and the riser was made of a 20mm diameter transparent rubber hose, which makes it easy to change the shape of the system. A schematic diagram of the test facilities is shown in Figure 2.

From the mixing point the flow goes trough the low-point at the bottom of the riser and depending on different conditions, slug flow may occur. At the top of the riser there is a separator, which leads the water to a reservoir. From there the water is pumped back into the system through the mixing point. The air is being let out through a small hole at the

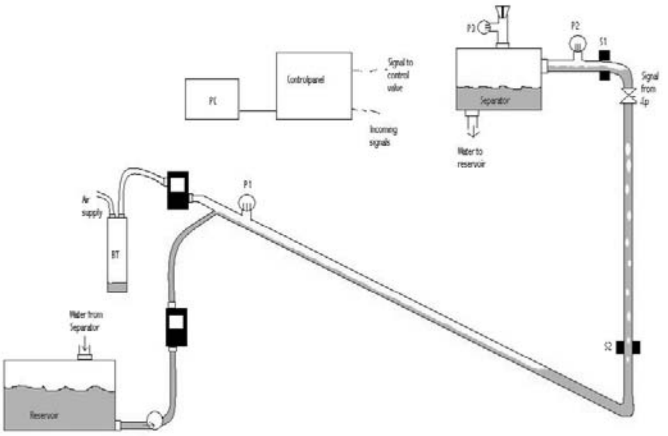


*Figure 2. Experimental setup*

top of the separator.

For slugging to appear there must be enough air in the system to blow the water out of the 1,5 meter long riser. This requires a certain amount of volume, which is accounted for by a buffer tank (BT) between the air supply and the inlet. The volume of the gas can be changed by partially filling this tank with water.

The flow rates of gas (Qair) and water (Qw) determines whether we will have slug flow in open loop operation or not. These flow rates are being measured upstream the inlet. Typically flow rates during an experiment are 1 l/min for the gas and 3 l/min for the water.

So far there are three pressure sensors located at different places in the loop. One is located at the inlet (P1) while the two others are topside measurements, located at the top of the riser (P2) and at top of the separator (P3). The latter is used for measuring the flow of air out of the separator.

Fiber optic sensors (S1, S2) give a signal depending on the amount of water in the hose where they are located. They can easily be mowed around to measure the holdup at different locations in the loop.

A control valve is placed at the top of the riser. A signal from the control panel sets the opening percentage of the valve.

The control panel converts the analog signals from the sensors into digital signals. These signals are then sent to a computer. The signals are continuously displayed and treated using Labview software. Depending on the control configuration, some of the measurements are used by the controller to determine the opening percentage for the control valve.

## 3. Controllability Analysis

Storkaas et al. (2003) have developed a simplified macro-scale model to describe the behavior of pipeline-riser slugging. The model has three states; the holdup of gas in the feed section ($m_{G1}$), the holdup of gas in the riser ($m_{G2}$), and the holdup of liquid ($m_L$). Using this model we are able to predict the variation of system properties such as pressure, densities and phase fractions.

In order for the model to fit the MiniLoop, it needs to be tuned. To do this we compare the bifurcation diagrams for the model and the Miniloop, plotted in Figure 3. The upper lines shows the maximum pressure at a particular valve opening and the lower line shows the minimum pressure. The two lines meet at around 20% valve opening. This is the point with the highest valve opening which gives stable operation when no control is applied. When Storkaas' model is properly tuned, the bifurcation point from the model will match the one from the experimental data. The dashed line in the middle shows the unstable steady-state solution, which is the desired operating line with closed-loop operation.

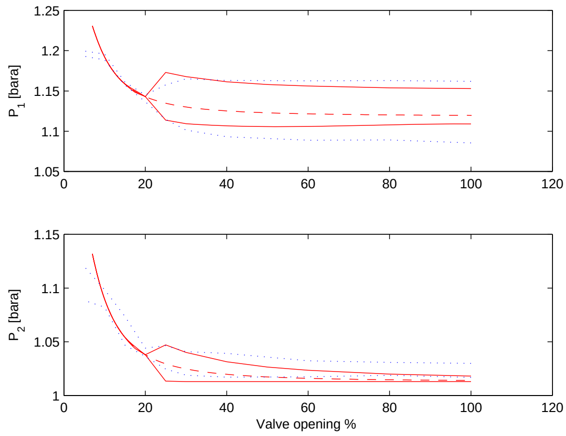


*Figure 3. Bifurcation diagrams from experimental data (dotted line) and Storkaas' model (solid line)*

When the model is tuned it can be used to perform a controllability analysis on the system. This way we can predict which measurements are suitable for control, thus avoiding slug flow. The analysis shows that the system consists of the poles given in Table 1.

*Table 1. Poles of the system for valve openings z=0.12 and z=0.25*

| z | |
|---|---|
| 0.12 | 0.25 |
| -20.3411 | -35.2145 |
| -0.0197 ± 0.1301i | 0.0071 ± 0.1732i |

Since all poles of the system are in the LHP when using a valve opening of 12%, this valve opening results in stable flow in the pipeline. However, when the valve opening is set to 25% we get a pair of RHP poles leading to riser slugging. This could also be predicted from the bifurcation diagram in Figure 3.
To stabilize the flow we have available several measurements. Four of these are topside measurements; pressure $P_2$, density $\rho$, volume flow $F_q$ and mass flow $F_w$. The fifth measurement is the inlet pressure, $P_1$. The zeros of the system using different measurements are given in Table 2.

*Table 2. Zeros of the system using different measurements at valve opening z=0.25*

| $P_1$ | $P_2$ | $\rho$ | $F_q$ | $F_w$ |
|---|---|---|---|---|
| -1.285 | 46.984 | 0.092 | -3.958 | -65.587 |
| | 0.212 | -0.0547 | -0.369 ± 0.192i | -0.007 ± 0.076i |

It is well known that stabilization (shifting of poles from RHP to LHP) is fundamentally difficult if the plant has a RHP-zero close to the RHP-poles. From this, we expect no

particular problems using $P_1$ as the measurement. Also, $F_q$ and $F_w$ could be used for *stabilization*, but we note that the steady-state gain is close to zero (due to zeros close to the origin), so good control *performance* can not be expected. On the other hand, it seems difficult to use $\rho$ or $P_2$ for stabilization because of presence of RHP-zeros.
From the controllability analysis we therefore can draw the conclusion that when using only one measurement for control, the inlet pressure $P_1$ is the only suitable choice.

## 4. Experimental results

The analysis showed that using the inlet pressure $P_1$ was the only possibility when using only one measurement for control. Based on this, a PI-controller was used to control the system using this measurement.
The MiniLoop was first run open loop for two minutes, with a valve opening of 30%. This is well inside the unstable area, as the bifurcation diagram shows. The result is the pressure oscillations plotted in Figure 4, which illustrates how the pressure and valve opening varies with time. Both experimental and simulated values using the simplified model are plotted.
When the controller is activated after two minutes, the control valve starts working. The flow is almost immediately stabilized, even though the average valve opening is still within the unstable area. It remains that way until the controller is turned of again after 8 min. When the controller is turned off, the pressure starts oscillating again.

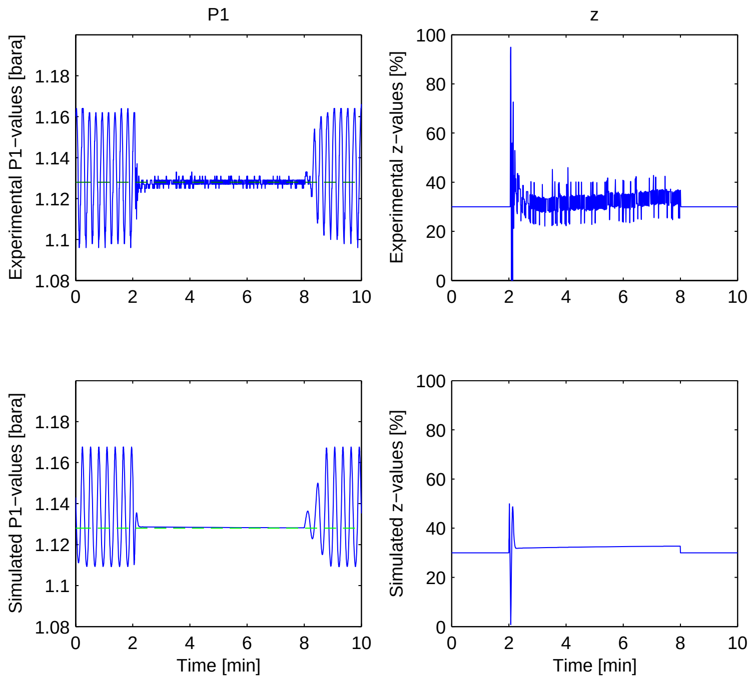


*Figure 4. Experimental and simulated results using a PI-controller*

From Figure 4 we see that the controller efficiently stabilizes the flow, confirming the results from the analysis. However, this measurement can be difficult to use in offshore installations because of its location.

Using other control configurations or measurements other than the ones analyzed in this paper might be the solution if there are only topside measurements available. The plan is to test out different ways to do this in the near future. The first possibility that will be explored, is using a cascade configuration involving the topside pressure $P_2$ and one of the flow measurements $F_w$ or $F_q$. Storkaas and Skogestad (2003) have proved theoretically that this works for another case of riser slugging.

## 5. Conclusion

From the controllability analysis it was found that using the bottom hole pressure was the only measurement of the five measurements analyzed, that could be used for controlling the system. The experiments confirmed that the model used for the analysis was good, and that using this measurement we where able to control the flow without problems.

We are, however, looking for other ways to control the flow because of the problems related to down hole measurements. When using some of the other measurements analyzed, we must use combinations of measurements in order to avoid the problems related to the zeros introduced.

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