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An autonomous approach for driving systems towards their limit: an intelligent adaptive anti-slug control system for production maximization

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Abstract: Anti-slug control in multiphase risers involves stabilizing an open-loop unstable operating point. Existing anti-slug control systems are not robust and tend to become unstable after some time, because of inflow disturbances or plant dynamic changes, thus, requiring constant supervision and retuning. A second problem is the fact that the ideal setpoint is unknown and we could easily choose a suboptimal or infeasible operating point. In this paper we present a method to tackle these problems. Our complete control solution is composed of an autonomous supervisor that seeks to maximize production by manipulating a pressure setpoint and a robust adaptive controller that is able to quickly identify and adapt to changes in the plant. The supervisor is able to automatically detect instability problems in the control loop and moves the system to a safer, stable operating point. Our proposed solution has been tested in a experimental rig and the results are very encouraging.

Keywords: Anti-slug control, adaptive control, autonomous control systems, production maximization

1. INTRODUCTION

The severe-slugging flow regime which is common at offshore oilfields is characterized by large oscillatory variations in pressure and flow rates. This multi-phase flow regime in pipelines and risers is undesirable and an effective solution is needed to suppress it (Godhavn et al., 2005). One way to prevent this behaviour is to reduce the opening of the top-side choke valve. However, this conventional solution reduces the production rate from the oil wells. The recommended solution to maintain a non-oscillatory flow regime together with the maximum possible production rate is active control of the topside choke valve (Havre et al., 2000). Measurements such as pressure, flow rate or fluid density are used as the controlled variables and the topside choke valve is the main manipulated variable.

From an economic point of view, we would like to have the lowest possible pressure (maximum valve opening) in the pipeline/riser system. This translates into low pressures at the bottom hole of the wells which maximizes the fluid inflow from the reservoir. However, as the pressure setpoint decreases the stabilization of the system becomes more difficult and, thus, the choice of the ideal setpoint is hard task. In fact, the ideal pressure setpoint is unknown and varies with the inflow conditions. Setting it too high reduces the production. Setting it too low may be infeasible (uncontrollable), leading to slug flow. Consequently, constant monitoring of the control system by the operators is needed.

Hence, we propose an autonomous supervisory system that safely drives the process in the direction of minimum pressure for production maximization. The main idea is to gradually decrease the pressure setpoint until just before the control performance is no longer acceptable due to slugging. The supervisor automatically assesses the performance and stability of the control loop and decides the direction in which we should change the pressure setpoint in order to ensure stable operation. For example, if we detect slow oscillations with growing amplitude in the output, the setpoint should be increased since it is safer and easier to stabilize.

Nonetheless, the standard linear controllers are typically designed for a given operating point and they may fail to give acceptable performance when the setpoint changes considerably. Another problem are the disturbances in the inflow, which greatly affect the dynamics of the plant.

For these reasons we implemented a robust adaptive anti-slug controller. For our application we chose the robust-adaptive output feedback control design method proposed by Lavretsky (2012). This method falls into the model-reference adaptive control category (Lavretsky and Wise, 2013) and fits well in our approach. This controller is able to quickly identify and adapt to changes in the plant dynamics in order to recover the desired performance.

Our complete control solution is composed of the autonomous supervisor and the robust adaptive slug control. It turns out the combination of these two elements results in a great synergy: the periodic setpoint changes triggered by the supervisor gives enough excitement in the system

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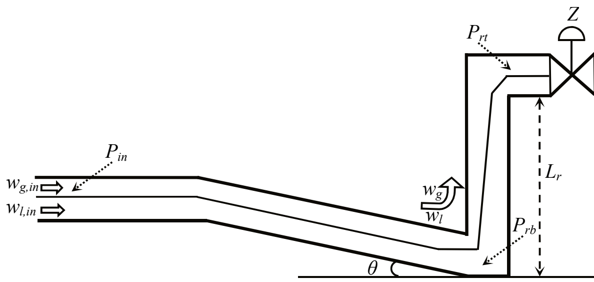

Fig. 1. Schematic representation of system

for the adaptation to work well; a well functioning adaptive controller allows the supervisor to push the system closer to the limit for a wide range of operating conditions.

Its worth to point out that this approach is very general and can be applied in a variety of applications with similar characteristics: dynamics change when approaching the (possibly unknown) operating limit of the system.

This paper is organized as follows. Section 2 describes the pipeline-riser system. The general approach that we proposed is described in Section 3, where Details about the supervisor and the adaptive controller are found. The results are presented in Section 4. Finally, we summarize the main conclusions and remarks in Section 5.

2. SYSTEMS DESCRIPTION

Fig. 1 shows a schematic presentation of the system. The inflow rates of gas and liquid to the system, $w_{g,in}$ and $w_{l,in}$, are assumed to be independent disturbances and the top-side choke valve opening ($0 < Z < 100\%$) is the manipulated variable. A fourth-order dynamic model for this system was presented by Jahanshahi and Skogestad (2011). The state variables of this model are as:

- m_{gp}: mass of gas in pipeline [kg]
- m_{lp}: mass of liquid in pipeline [kg]
- m_{gr}: mass of gas in riser [kg]
- m_{lr}: mass of liquid in riser [kg]

The four state equations of the model are

$$\dot{m}_{gp} = w_{g,in} - w_g \tag{1}$$

$$\dot{m}_{lp} = w_{l,in} - w_l \tag{2}$$

$$\dot{m}_{gr} = w_g - \alpha w \tag{3}$$

$$\dot{m}_{lr} = w_l - (1 - \alpha) w \tag{4}$$

The flow rates of gas and liquid from the pipeline to the riser, w_g and w_l, are determined by pressure drop across the riser-base where they are described by virtual valve equations. The outlet mixture flow rate, w, is determined by the opening percentage of the top-side choke valve, Z. The different flow rates and the gas mass fraction, α, in the equations (1)-(4) are given by additional model equations given by Jahanshahi and Skogestad (2011). In this paper we used the linearized version of this model for the control design methods. Alternatively, empirical low-order models could have been used (Jahanshahi and Skogestad, 2013).

3. AN AUTONOMOUS APPROACH FOR DRIVING SYSTEMS TOWARDS THEIR LIMIT

Here we propose an autonomous control system to drive a process towards its operational limit. Our solution is composed of two main elements:

- supervisory system that overlooks the control loop, assess stability and performance and makes a decision on which direction (increase or decrease) the setpoint should move. In our application, the strategy is to gradually reduce the pressure setpoint until a stability problem is detected (e.g., slow oscillations start to build-up). At this point the supervisor should move the system to a safer operating point (increase setpoint).
- a robust adaptive controller that regulates the system to the setpoint specified by the supervisory controller. The controller must be able to identify changes in the plant dynamics and compensate for it to give acceptable closed-loop performance in a wide range of operating conditions.

We believe that the combination of frequent setpoint changes by the supervisor with and adaptive control scheme can be very fruitful because the periodic setpoint changes triggered by the supervisor gives enough excitement in the system for the adaptation to work well; a well functioning adaptive controller allows the supervisor to push the system closer to the limit compared to linear controllers.

3.1 Supervisory control

A key component in an autonomous supervisor is the ability to quickly detect problems in the control loop. In our application the main problem is the appearance of slugging flow which is characterized by growing (slow) oscillations in the pressures and flows with a certain frequency. Such oscillations are a signal that the controller is having problems to control the process at the given operating conditions and should move to a safer setpoint. Algorithm 1 exemplifies a basic supervisory scheme for the anti-slug control problem. P_{sp} is the pressure setpoint and ΔP_{sp} represents the size of the steps. The pressure can be measured at any point of the system (e.g. riser base or riser top). Note that the amplitude of the step when increasing or decreasing the setpoint may be different.

The basic idea is to periodically check for slow oscillations in the system and decrease the setpoint only if nothing is detected. On the other hand, we should quickly increase the setpoint if the amplitude of the oscillations are starting to grow. In this case, it could be desirable to reset the adaptation parameters to the previous good values using, for instance, a look-up table.

For a practical application, however, many other safeguards must be included. For example, if a major disturbance occurs, the controlled variable may drift away from the setpoint very rapidly and the oscillation detection system may fail to perceive in time. In order to quickly detect these major problems a second, independent check function must be implemented. In our case we periodically analyse the mean control error over a short time horizon.