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Nonlinear control solutions to prevent slugging flow in offshore oil production

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ABSTRACT

Feedback control is an efficient and economical solution to prevent slugging flow regimes in offshore oil production. For this, a choke valve at the topside platform is used as the manipulated variable to control the pressure or the flow rate in the pipeline. The primary challenge for anti-slug controllers is robustness. The lack of robustness is due to changes in inflow conditions, the process nonlinearity, and modeling errors. In particular, the nonlinearity combined with an inverse response behavior makes the control of the topside pressure more difficult. We have conducted nonlinear and linear analysis and evaluated four control designs experimentally with both subsea and topside pressures. The control designs are (1) feedback linearization with measured outputs, (2) gain-scheduling IMC (internal model control) based on identified model, (3) PI control with an adaptive gain based on a static gain model, and (4) state feedback with state estimation by a nonlinear high-gain observer. We compared the robustness of these controllers regarding tolerance to time delay, change of the operating point and inflow disturbances. All the controllers could handle 30% step changes (disturbances) in inflow rates and remained stable. The gain-scheduling controller was more robust against time delay than the other controllers. By applying the high-gain observer, the stabilization was achieved in an acceptable range when only the topside pressure was available. However, the observer diverges when using a subsea pressure measurement which from a controllability point of view should be the easiest controlled variable. Nevertheless, this result agrees with the observability theory.

1. Introduction

In offshore oil production, a multi-phase mixture of oil, gas and water is transported from the producing oil wells at the seabed to the topside facilities through subsea pipelines and risers. Under certain inflow conditions (*i.e.* low inflow rates and low pressure), slugging flow regimes occur in the pipeline-riser systems. Such flow regimes are characterized by severe flow and pressure oscillations. These flow conditions cause numerous operational problems in oil production, *e.g.* poor separation, overflow of inlet separators and unwanted gas flaring [1].

The conventional solution to mitigate slugging flow is to reduce the opening of the topside choke valve (choking), but this increases the back-pressure on the producing oil wells and decreases the production rate. Therefore, a solution that guarantees stable flow together with the maximum possible production rate is desirable.

Feedback control has been shown to be an effective strategy to eliminate slugging [2–4]. The topside choke valve is usually used as the control input to regulate pressure at a given pressure setpoint. Such a system is referred to as "anti-slug control" aiming to stabilize the flow under operating conditions that, without control, would lead to slugging [5]. Usually, a subsea pressure measurement is used as the controlled variable. The subsea pressure sensor can be installed at the riser base (P_{rb}) or upstream towards the pipeline inlet (P_{in}). Controlling the pressure measured from the riser top (P_{rt}) is an alternative which is simpler from a practical point of view.

Although the control structures used for this purpose are simple, the existing anti-slug controllers are not robust in practice over long periods of operation. The robustness issues are mainly due to varying inflow conditions, *i.e.* pressure, inflow rate and GOR (gas/oil ratio). The robustness issues are further emphasized in the following personal communication from John Morten Godhavn who has a lot of industrial experience [6]: "The slugging potential and flow regime change over time. For example, the production engineers may add a new well to the manifold at the pipeline inlet, or they

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may close or open an incoming well stream for the production optimization reason. By adding a well, the total inflow rate may increases such that there will be no need for the slug control anymore. Then, one year later, the GOR may change, or the flow rate may increase or decrease. As a result, the system will experience a very different type of slugging. Therefore, it is not possible to develop a slug controller that can be left alone to handle all kinds of flow regimes, unfortunately. Changes in the operating conditions will require tight follow-up from someone who understands both multiphase flow and feedback control to update the controller settings. Such issues are not explained in the public domain literature. Most papers either present simulations or success stories".

The nonlinearity of the process is a problem for a linear controller because the process gain changes drastically at different operating conditions, and the controller needs to be re-tuned. The nonlinearity of the process can be counteracted by nonlinear model-based controllers or by a gain-scheduling of linear controllers. Also, the effective time delay caused by long flowlines is another problematic factor for stabilizing control.

The primary objective of our research is to design robust anti-slug control systems. A robust controller requires less frequent re-tuning. The focus of this article is on nonlinear control solutions to counteract the process nonlinearity. First, we design a feedback linearization controller based on a mechanistic model. This controller uses two measured outputs (P_{rb} and P_{rt}). Another approach, in which the mechanistic model is not directly used for the control design, is to identify an unstable model of the system by a closed-loop step test. We use the identified model for an IMC (internal model control) design to control the inlet pressure (P_{in}). We construct gain-scheduling using three IMC controllers to cover a wide operational range. Next, we consider adaptive PI control where the adaptation is based on a simple model for the static nonlinearity of the process. Here, the controlled variable of the feedback is the inlet pressure (P_{in}), and the static process gain is updated from the valve opening value (Z) and the topside pressure (P_{rt}) which are always available.

Stabilizing control using only the topside pressure measurement (P_{rt}) is not robust; this has been investigated based on a linear controllability analysis [7]. If only the topside pressure measurement is available, a conventional control solution is to design an observer to estimate the states of the system including the subsea pressure, and then use these estimates for control [8,9]. Although we know that the observer and the state feedback design cannot be generalized for all control application, we will investigate if this solution can recover some stabilizability and robustness when no subsea measurement is available.

Some of the results provided in the paper have been partially presented in [10]. In this article, we add a system analysis and the adaptive control design, and we discuss the results in detail.

This article is organized as follows. A mechanistic model for the severe slugging flow is introduced in Section 2, and the model is used for analysis in Section 3. The four control designs are presented in Section 4. The experimental results are shown in Section 5 and discussed in Section 6. Finally, the main remarks and conclusions are summarized in Section 7.

2. First principle model

We have developed a dynamic model for riser slugging based on mass and momentum balances [5]. This model is able to capture the main dynamics of the slugging flow regime, and it is of good fit with the detailed commercial simulator OLGA® [11] and experiments. The model is described by only four ODEs with soft nonlinear functions which make it suitable for controller design.

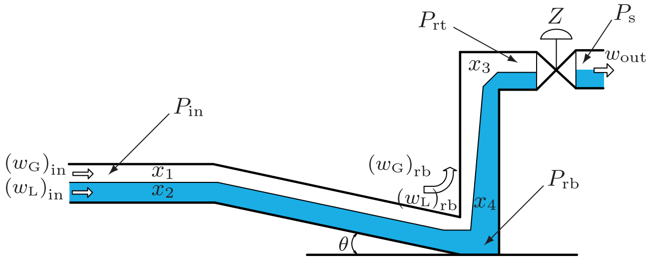

Fig. 1. Schematic presentation of the system.

2.1. Summary of the four-state model

Fig. 1 shows a schematic presentation of the model. The state variables of this model are

- x_1[kg]: mass of gas in pipeline,
- x_2[kg]: mass of liquid in pipeline,
- x_3[kg]: mass of gas in riser,
- x_4[kg]: mass of liquid in riser.

The four state equations of the model are the following mass balances:

$$\dot{x}_1 = (w_{\text{G}})_{\text{in}} - (w_{\text{G}})_{\text{rb}}, \tag{1}$$

$$\dot{x}_2 = (w_{\text{L}})_{\text{in}} - (w_{\text{L}})_{\text{rb}}, \tag{2}$$

$$\dot{x}_3 = (w_{\text{G}})_{\text{rb}} - \left(\alpha_{\text{G}}^{\text{m}}\right)_{\text{rt}} w_{\text{out}}, \tag{3}$$

$$\dot{x}_4 = (w_{\text{L}})_{\text{rb}} - [1 - \left(\alpha_{\text{G}}^{\text{m}}\right)_{\text{rt}}] w_{\text{out}}. \tag{4}$$

The inflow rates of gas and liquid to the system, $(w_{\text{G}})_{\text{in}}$ and $(w_{\text{L}})_{\text{in}}$, are assumed to be independent disturbances with known nominal values. The flow rates of gas and liquid from the pipeline to the riser, $(w_{\text{G}})_{\text{rb}}$ and $(w_{\text{L}})_{\text{rb}}$, are described by virtual valve equations (A.30), (A.33). The outlet mixture flow rate, w_{out}, is determined by the opening percentage of the topside choke valve, Z, which is the manipulated variable of the control.

Although (1)–(4) seem to be linear, calculation of the flow rates and the mass fraction $\left(\alpha_{\text{G}}^{\text{m}}\right)_{\text{rt}}$ involves several nonlinear equations (*e.g.* valve equations and frictions). See Appendix A for the complete set of the model equations.

2.2. Model fitting

The four-state model can be partly configured based on dimensions and other physical properties (*e.g.* fluid properties) to fit it to a given pipeline-rise system. In addition, four fitting parameters are included in the model for the purpose of fine-tuning. The fitting procedure is described in [5]. In this work, the four-state model has been fitted to data from experiments and simulations using the OLGA simulator. The experimental setup is described in Section 5.1.

The open-loop system has a stable (non-slug) flow when Z is smaller than 15%, and it switches to unstable (slugging) flow conditions for larger valve openings. The bifurcation diagram describes steady-state process values and the minimum and maximum values when the flow is oscillatory [7]. This diagram may be obtained experimentally or from a more detailed model (*e.g.* OLGA). Such diagrams are used as the reference to fit the model (Fig. 2).

In Fig. 2, the minimum and maximum values for the four-state model deviate from those of OLGA and the experiment. These differences are due to measurement noises and un-modeled dynamics such as hydrodynamic slugging, which the four-state model is not able to describe. From a control point of view, the steady flow