Slug-flow Control in Submarine Oil-risers using SMC Strategies ⋆

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Abstract: In this paper we propose different Sliding Mode Control (SMC) strategies to control slug-flow oscillations in submarine oil-risers. The main idea is to design a switching control law that induces a sliding bifurcation on the system, changing its dynamics and, in this way, controlling the amplitude of a limit cycle. Simulation results were obtained using OLGA Scandpower software in order to compare the different SMC strategies.

Keywords: Production oil system, Submarine oil-riser, Slug-flow control, Non-smooth dynamical systems, Sliding Mode Control, washout filter

1. INTRODUCTION

Transportation of multiphase fluid (oil, gas and water) is an important task in the oil industry. Nowadays, there is a trend to increase the number of satellite wells and the length of risers between clusters of wells and off-shore production systems. Besides, the increasing depths of oil wells produces several new multiphase transport problems, see Storkaas and Skogestad (2004), Storkaas (2005). In this scenario a common problem is the phenomena so called slug-flow characterized by the intermittent axial distribution of gas and liquid. The pressure and flow rate oscillations induced by the slug-flow can provoke several undesired effects on the surface equipments. These types of disturbances can cause serious problems in the input of the multiphase flow separator, deteriorating the separation quality and causing level overflow (Godhavn et al. (2005)). In short, the slug-flow phenomena in submarine risers cause several problems to the oil off-shore industry. The suppression of this type of oscillations by means of feedback automatic control methods can be applied to stabilize the flow in risers and, consequently, minimize the problems on the separator. At the same time, two other benefits can be obtained: (i) in cases where the oil is pumped from sea bottom, energy consumption is minimized; (ii) in cases of risers connected to wells with natural or artificial lift flows, higher production is obtained by minimizing the pressure in front of the well perforated zones.

A schematic diagram of a riser used in an oil production off-shore system is shown in Fig. 1 with parameters shown in Table 1. This system was simulated in OLGA [1].

In Fig. 1, bottom and top riser pressures P_1 and P_2, respectively, are measured in [Pa] units and the control action is applied on the production choke. Modelling this system is quit complex since it involves partial differential equations. A simplified third order dynamical model developed in ordinary differential equations can be found in Storkaas and Skogestad (2004), Storkaas (2005). The bifurcation diagram considering the choke opening as a bifurcation parameter (see Fig. 2), was obtained based on OLGA data simulations for a mass flow rate entering the riser equal to $5Kg.s^{-1}$ and a pressure separator of 5.10^6Pa. The bifurcation diagram of Fig. 2 is qualitatively similar to the diagram shown in Storkaas and Skogestad (2004). The stable and unstable equilibria manifold are depicted in Fig. 3. In this figure we show also the curves corresponding to maximal and minimum values of the limit cycle. A projection

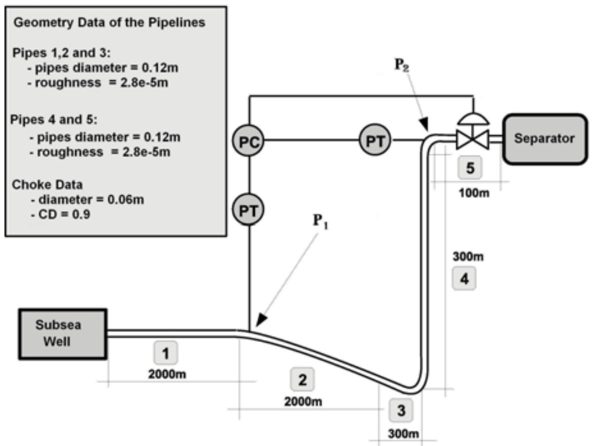

Fig. 1. Oil-riser system set-up simulated in OLGA.

Table 1. Parameter values of the riser setup.

Parameter	value	unit
Mass flow rate entering the riser	5	$Kg.s^{-1}$
Separator pressure	5.10^6	Pa
Gas void fraction	5	%
Temperature in the riser output	22	^oC
Temperatura in the well	62	^oC

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[1] Multiphase flow software simulation commercialized from Scandpower.

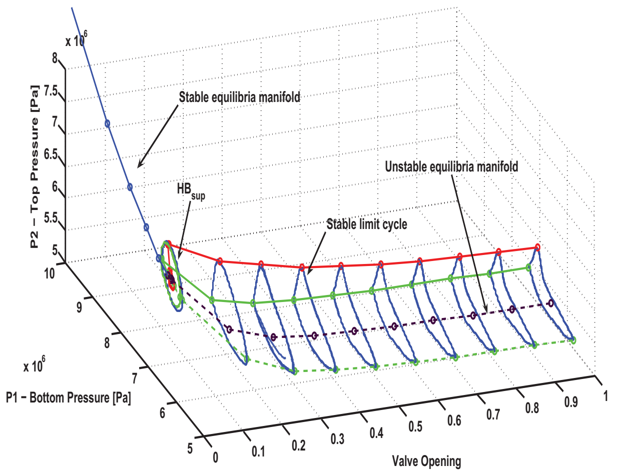

Fig. 2. Bifurcation diagram considering the choke opening as the bifurcation parameter. A stable limit cycle undergoes from a supercritical Hopf Bifurcation (HB_{sup}).

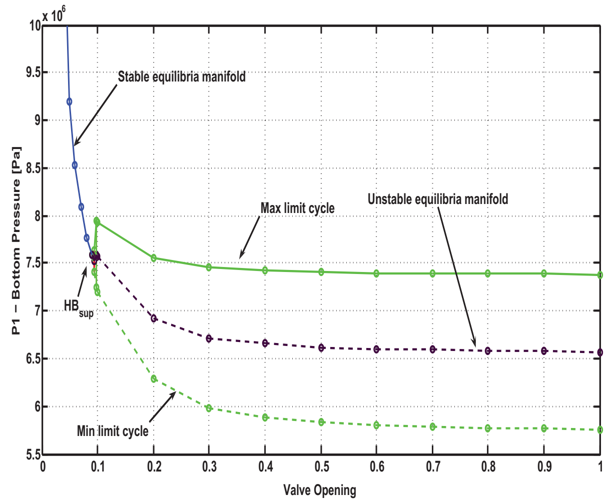

Fig. 3. Bifurcation diagram in $(u(t), P_1)$ plane.

of the limit cycles for different choke openings in the (P_1, P_2)-plane is shown in Fig. 4. As we can observe in this picture, the relation between P_1 and P_2 pressures on the stable (unstable) equilibria manifold can be approximated by a straight line. As can be seen in Figs. 2-4, a supercritical Hopf Bifurcation takes place, at the point HB_{sup} in the diagram, giving rise to a stable limit cycle. Thus, without active feedback control it is necessary to operate the system with choke opening below 10% in order to avoid output system oscillations. The pressure drop around the choke rises for low choke opening and this pressure drop is added to riser's bottom. High pressure for the same mass flow rate means higher energy consumption for sea floor pump applications. On the other hand, risers connected to natural or artificial lift wells may affect the pressure in front of the perforated zones leading to less oil production flow rate. Whatever the case it is desirable to have a steady flow with minimum pressure drop in the surface choke.

Several linear control laws to prevent slug-flow oscillations in submarine oil-risers have been proposed in different works, see

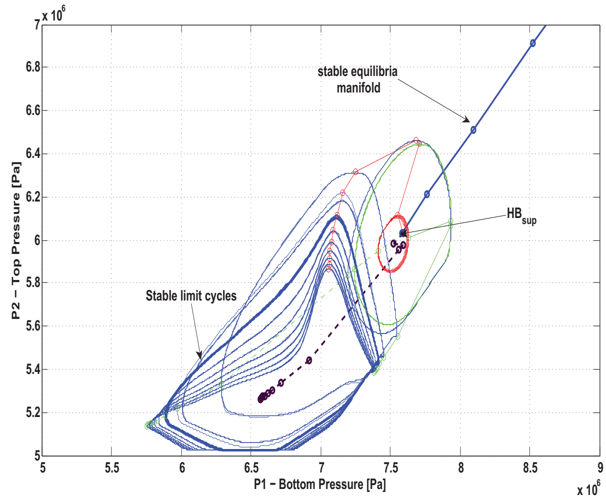

Fig. 4. Bifurcation diagram in (P_1, P_2) plane.

for instance Storkaas (2005), Godhavn et al. (2005). Linear controllers are only local solutions for this complex non-linear control problem. In this paper, as an alternative solution, we propose different non-linear control systems based on the Sliding Mode Control (SMC) theory.

The paper is organized as follows. In Section 2, the Proportional-Integral (PI) control law is revisited showing that it is not robust under disturbances in the input riser flow rate. In Sections 3 and 4, we propose different SMC strategies to control slug-flow oscillations. Our slug SMC washout strategy is presented in Section 5. Finally we discuss some of the limitations of these switching strategies and propose future improvements.

2. REVISITING THE PI CONTROL STRATEGY TO SUPPRESS SLUG-FLOW

In this Section we show by means of simulation results that the PI control law is not robust to disturbances in the input riser flow rate. A simulation test was made to evaluate the efficiency of the PI control. The PI control law is given by

$$u(t) = k_c[e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau],$$

where $k_c = -7.92 \cdot 10^{-6} Pa^{-1}$, $T_i = 49.5s$, $e(t)$ is the error and the process variable is the pressure P_1. The PI discrete form implemented is given by

$$u(k) = u(k-1) + s_0 e(k) + s_1 e(k-1)$$

where $s_0 = k_c(1 + \frac{T_s}{T_i})$, $s_1 = -k_c$, $T_s = 1s$ is the sampling time and T_i is the integral time. PI control tuning was made using simple rules of adjusting since no mathematical model of reduced order for control design was available. The simulation setup was defined as:

(1) the choke opening is fixed at 20% and the corresponding operating point calculated from the equilibria manifold curve is $(P_1^*, P_2^*) = (6.93 \cdot 10^6[Pa], 5.56 \cdot 10^6[Pa])$;
(2) at $5000s$ the control is switched ON;
(3) a disturbance in the input riser flow rate is applied at $15000s$;
(4) the control is switched OFF at $25000s$.

Two flow rate disturbances were defined (i) from $5Kg.s^{-1}$ to $3.5Kg.s^{-1}$ and (ii) from $5Kg.s^{-1}$ to $3Kg.s^{-1}$. We use the

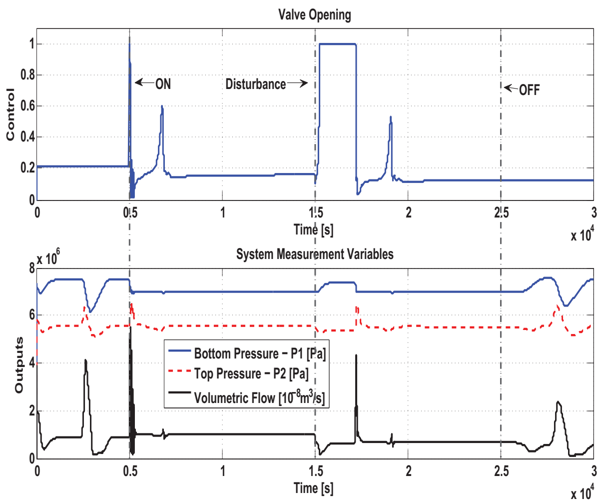

Fig. 5. System time response under *PI* control for a flow rate disturbance from $5Kg.s^{-1}$ to $3.5Kg.s^{-1}$.

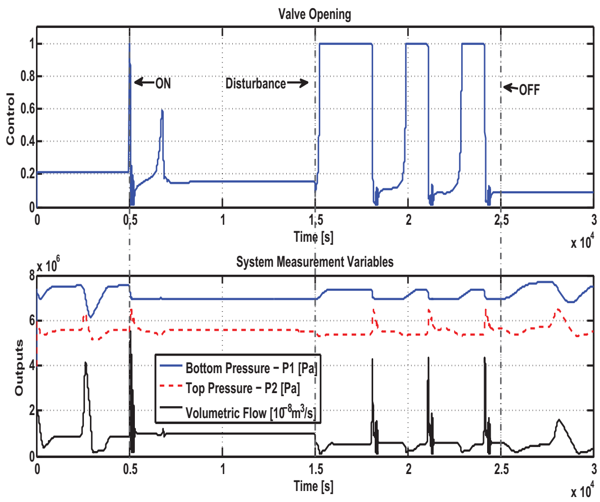

Fig. 6. System time response under *PI* control for a flow rate disturbance from $5Kg.s^{-1}$ to $3Kg.s^{-1}$.

previous simulation setup in order to obtain comparative results between the different slug control strategies.

Simulation results using the PI control are shown in Fig.5 for the first disturbance and in Fig.6 corresponding to the second disturbance. As can be seen, the PI control reject the first perturbation but it is not robust for the second disturbance.

In order to tackle this problem for large flow rate disturbances, three different Sliding Mode Control (SMC) strategies are proposed in the following Sections.

3. SLUG SMC STRATEGY

The main idea is to design a Sliding Mode Control (SMC) law (switching system) that induces a grazing-sliding bifurcation (see Angulo et al. (2005a)) on the system, changing its dynamics and, in this way, the amplitude of the target limit cycle is controlled. This type of non-smooth bifurcation introduces partial sliding motion along a sliding surface, reducing or suppressing the amplitude of the undesired limit cycle. In order to explain these ideas, consider a general system defined by

$$\dot{x} = F(x, u(x)) \tag{1}$$

where $x \in \mathbb{R}^n$ is the state vector of dimension n, and $u(x) \in \mathbb{R}$ is the control signal. The function $F(x) = (F_1, F_2, ..., F_n) : \mathbb{R}^n \rightarrow \mathbb{R}^n$, represents a non-smooth continuous system. We also assume that as a result of a Hopf bifurcation (continuous or not, see di Bernardo et al. (2008)), the system exhibits a steady state oscillatory behavior, where a stable limit cycle is the solution from (1).

The grazing-sliding bifurcation to suppress a limit cycle occurs when the limit cycle is crossed by a sliding surface that generates a grazing-sliding non-smooth transition where part of the trajectory of the limit cycle stands on the sliding surface as shown in Fig. 7.

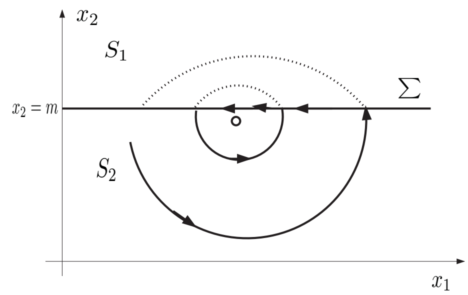

Fig. 7. Grazing-sliding bifurcation induced in the system.

For example, on a system with dimension 2, we consider a region S_1 of the form

$$S_1 := \{x = (x_1, x_2) : x_2 > m\}$$

for arbitrary m, being

$$\Sigma := \sigma(x) = \{x = (x_1, x_2) : x_2 = m\}$$

and

$$S_2 := \{x = (x_1, x_2) : x_2 < m\}.$$

With the variation of m, a grazing-sliding bifurcation occurs and the amplitude of the limit cycle is reduced or even eliminated.

Thus, the sliding mode control suggested is

$$u = u_0 + \Delta u \ \mathrm{sgn}(\sigma(x)) \tag{2}$$

where $\sigma(x) = 0$ is the sliding surface, a function of the system's states that allow the changing of its dynamics; u_0 is the value of the control variable at the operating point and Δu is the maximum value that the control variable can assume from u_0.

The function $sgn(\cdot)$ can be defined as

$$\mathrm{sgn}(\sigma(x)) = \begin{cases} -1, & \text{if } \sigma(x) < 0; \\ 1, & \text{if } \sigma(x) > 0. \end{cases} \tag{3}$$

or

$$\mathrm{sgn}(\sigma(x)) = \begin{cases} 0, & \text{if } \sigma(x) < 0; \\ 1, & \text{if } \sigma(x) > 0. \end{cases} \tag{4}$$

Applying the above equations, we propose the following control law given by

$$u = u_0 + \Delta u \ \mathrm{sgn}(\sigma), \tag{5}$$

$$\sigma(P_1, P_2) = P_2 - P_1 + \beta, \tag{6}$$

where $\beta = P_1^* - P_2^*$; $\Delta u = u_0 - u_{min}$; u_0 is the desired choke opening and u_{min} is the control value at the Hopf Bifurcation point. The switching surface is defined as $P_2 = P_1 - \beta$ and we define the $sgn(\cdot)$ to close the choke whenever $\sigma > 0$. The choke opening bias u_0 is defined at the riser desired operating point. At this point P_1^*, P_2^* are defined on the equilibria manifold curve, for a given mass flow rate of the riser input, as shown in Fig. 3. Choosing the surface choke opening bias u_o has to consider two factors. For one the value should be high enough in order to ensure a minimum pressure drop around the choke. On the other hand the bias should not be too far from values which can cause high pressure drops in order to answer quickly to disturbances. Choke opening close to 100% cause minimum pressure drop but depending on the choke characteristics a significant choke pressure drop can only be obtained for values smaller than 10%.

The control strategy can be interpreted as a mechanism to force an hypothetical steady flow rate which would be obtained without the slug flow behavior. For a constant input gas and liquid mass flow rate the pressure P_1 could be expressed as $P_1 = P_2 + \beta$ where β would take into account the gravity and friction terms of a pseudo stable flow. For instance, the simplest model is the homogeneous model given by

$$P_1 - P_2 = \frac{m_{gr} + m_{lr}}{A} g + \frac{f \bar{\rho} \bar{v}^2}{2 d_r} h, \tag{7}$$

where A is the section of the pipe; m_{gr} and m_{lr} are the mass of gas and mass of liquid in the riser; $\bar{\rho}$ is the mean density of the flow; $\bar{v}$ is the mean velocity of the flow in the riser; h is the height of the riser; f is the friction function; d_r is the diameter of the pipeline. In (7), first term corresponds to the gravity term and the second is the friction term.

Anytime the relationship is violated action is taken in the choke opening to force the desired P_1, P_2 relationship. Obviously this is done in a way that provides a desired choke opening which minimizes P_1 and consequently the energy used to lift the gas and liquid flow-rates entering the riser.

Time open-loop system responses are shown in Fig. 8. At $t = 5000s$ the proposed control system is turned on. At $t = 15000s$, a disturbance in the flow rate (from $5Kg.s^{-1}$ to $3.5Kg.s^{-1}$) was applied. It can be observed in Fig. 8 and Fig. 9 where the amplitude of the oscillations are decreased around the operating point when the control is switched on. As can be seen in Fig. 8, after the control is switched off, at $t = 250000s$, the oscillations back to the system. State space diagram, in (P_1, P_2)-plane, is depicted in Fig. 9.

The proposed SMC works well for small input riser flow rate disturbances but the control action switches permanently to maintain the equilibrium at the operating point.

4. A MODIFIED SLUG SMC STRATEGY

The SMC strategy development in Section 3 is not efficient to suppress pressure or flow oscillations in the riser since the control action switches permanently to maintain the equilibrium at the operating point. This would be very detrimental to the choke integrity. Another desired control characteristic is to be able to suppress the oscillations while keeping the choke nearly 100% opened. This represents significant less power needed to pump the multiphase fluid to the surface. In this Section, we propose a change in the control algorithm to minimize the switching in the control signal. The idea is to combine two control laws (i) the control used in Section 3 and (ii) a discrete form of the PI control law as used in Section 2 by means of a convex function as

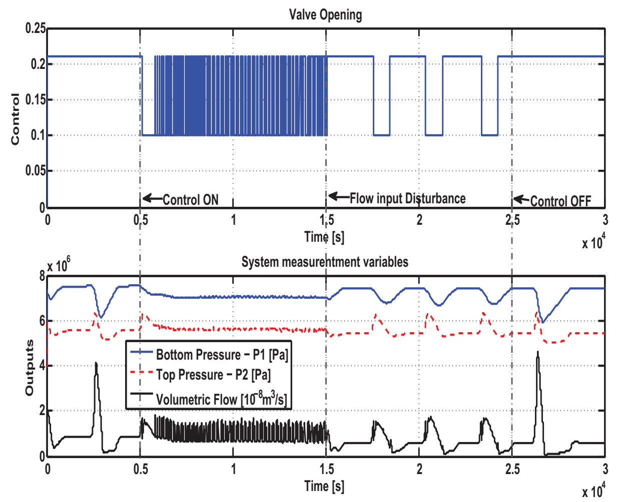

Fig. 8. Time system response (open-loop and with feedback control) with the SMC control strategy. a) choke opening; b) states of the system.

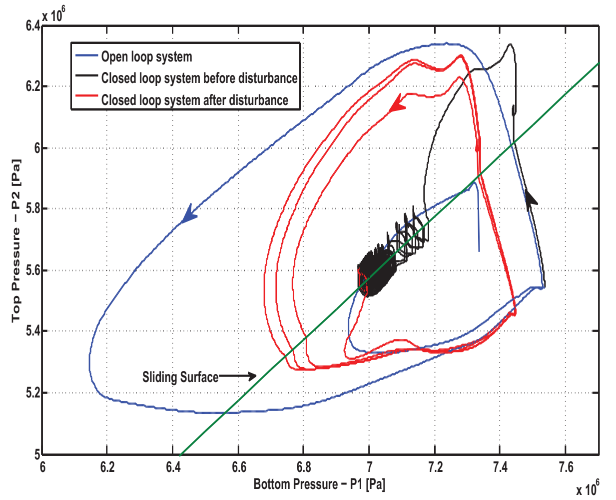

Fig. 9. State space diagram in (P_1, P_2)-plane

$$u(t) = \mu \; u_{SMC} + (1 - \mu) \; u_{PI}, \tag{8}$$

$$u_{SMC} = u_0 + \Delta u \; sgn(\sigma), \tag{9}$$

where

$$\sigma = P_2 - P_1 + \beta.$$

$$u_{PI}(k) = u_{PI}(k-1) + s_0 \; e(k) + s_1 \; e(k-1), \tag{10}$$

where u_{SMC} is the switching control law given by (9) and u_{PI} is the PI control (10), with $e(k) = P_1^*(k) - P_1(k)$.

The parameter $\mu = \mu(P_1, P_2)$ provides a smooth transition between the two control laws in such a way that if the trajectories are far away the equilibrium point then μ is close 1; otherwise μ is close to 0. It is defined as

$$\mu = \frac{1}{1 + e^{\gamma(\lambda - \delta)}} \tag{11}$$

$$\lambda(P_1, P_2) = (\frac{P_1}{P_1^*} - 1)^2 + (\frac{P_2}{P_2^*} - 1)^2$$

where P_1^* is the operating point for bottom pressure and P_2^* is the desired value for the input choke pressure. Parameter values of (9), (10) and (11) are given in Table 2. Parameter

Table 2. Control law parameters.

Parameter	value	unit
u_0	0.2	
Δu	0.12	
s_0	$-8.08 \cdot 10^{-6}$	Pa^{-1}
s_1	$7.92 \cdot 10^{-6}$	$Pa-1$
γ	$8/\delta$	
δ	0.008	

β is defined as $\beta = P_1^* - P_2^*$. The system response with the proposed control law to a disturbance of the well mass flow rate is shown in Fig. 10 and the space state diagram is depicted in Fig. 11. The sample time was chosen as $T_a = 1s$. At

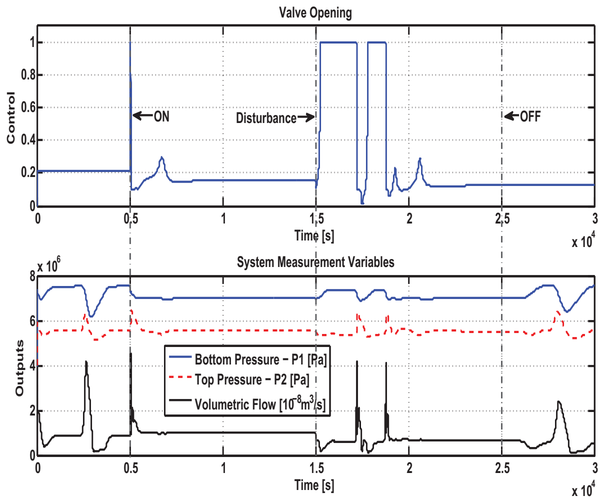

Fig. 10. Control and output system responses with the modified control law (8) for a disturbance input.

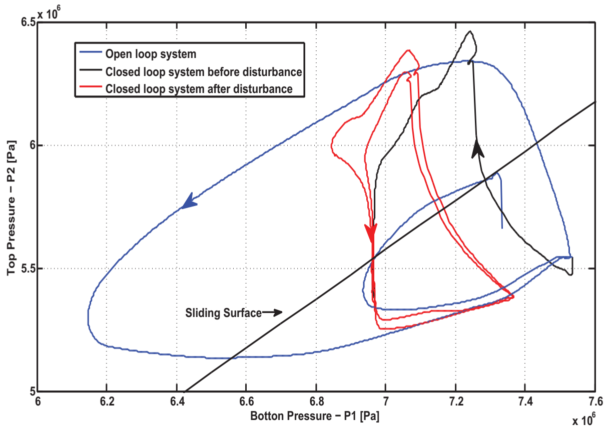

Fig. 11. State-space diagram of the system with the modified control law (8).

$t = 15000s$, the mass flow rate coming from the well is reduced from $5kg/s$ to $3.5kg/s$. This disturbance changes the operating process conditions. The proposed SMC control strategy control the system reduce the amplitude of the oscillations.

At $t = 25000s$, the control is turned off and the system starts to exhibit pressure and flow signal oscillations again. As can be seen the oscillations are back since the choke opening value is now in the instability region.

A disadvantage using the SMC algorithm discussed in this Section is that it is not possible to stabilize the system for large flow rate disturbances.

5. SLUG WASHOUT SMC CONTROL

All approaches presented so far for the slug control have used set-points to derive the control law. These strategies have a problem when there are changes in the fluid mass flow rate entering the riser. Even a stabilized flow rate will exhibit a different value both for P_1 and P_2 since higher mass flow rate will result in higher gravity and friction terms on the riser pressure drop as well as higher pressure drop in the surface choke. For the sliding mode control keeping the set-points for changes in the input mass flow rate means to request the system to operate in a limit cycle not sufficiently collapsed or to ask for an infeasible stabilized flow.

Since the practical objetive is to stabilize the flow keeping the surface choke with a minimum pressure drop, the idea of pressure set-point looses significance. One could say that the control problem is well solved if the pressures and flow rates do not oscillate while the surface choke is kept opened well above the opening which characterizes the beginning of the limit cycle. The idea is to develop a control strategy which supres the oscillation while keeping the choke opening operating around a desired opening value. If the oscillations are suppressed the resultant pressures will be a consequence of the input mass flow rate, fluid characteristics and the system geometry.

In order to attend the former constraints, we propose, in this Section, a new SMC strategy to reject mass flow rate input riser perturbations based on washout filters. Washout filters are intensively used to control chaotic systems by means of techniques based on bifurcation theory Wang and Abed (1995) and in flight control systems Lee and Abed (1991). Recently, washout filters were applied to power electronic converters in conjunction with SMC controllers in order to reject load disturbances Cunha and Pagano (2002). A washout filter is a high-pass linear filter that washes out steady-state inputs while passing transient inputs. The use of washout filters ensures that all the equilibrium points of the original system are preserved in the controlled system, i.e., their location remains unchanged.

The transfer function of a typical washout filter is given by

$$G_F(s) = \frac{s}{s+w} = 1 - \frac{w}{s+w},$$

where w denotes the reciprocal of the filter time constant which is positive for stable filter. We assume that it is possible to filter the inductor current x to achieve a new signal x_F and define an auxiliary variable z so that it is satisfied the output equation

$$x_F = x - z.$$

Then the effect of the washout filter can be represented by means of an additional differential equation, namely

$$\frac{dz}{dt} = w(x - z). \qquad (12)$$

In our problem, we use two washout filters in order to filter the signals P_1 and P_2 in such a way that

$$\dot{z}_1 = w_1(P_1 - z) = w_1\tilde{p}_1$$

$$\dot{z}_2 = w_2(P_2 - z) = w_2\tilde{P}_2$$

where $\tilde{p}_1$, $\tilde{p}_2$ are the bottom and top filtered pressures, $w_1 = \frac{2\pi}{5}f_1$ and $w_2 = \frac{2\pi}{5}f_2$ are washout filter constants designed from the oscillatory frequencies f_1, f_2 measurement from the OLGA data simulation.

$$u_{WSMC} = u_0 + \Delta u \; sgn(\sigma), \tag{13}$$

where

$$\sigma(\tilde{P}_1, \tilde{P}_2) = \tilde{P}_2 - \tilde{P}_1. \tag{14}$$

Note that (14) is similar to (6) but now the parameter β is equal to zero. The sliding surface is now defined as $\tilde{P}_2 = -\tilde{P}_1$ and it does not depend on the operating point.

At $t = 10000s$ automatic control is turned on and at $30000s$ a well flow rate is reduced from $5kg/s$ to $3kg/s$.

At $50000s$ the control is again turned off and the system back to the oscillatory behavior. Simulation results are shown in Fig. 12. The state-space diagram in $(P_1 - P_2)$-plane is shown in Fig.

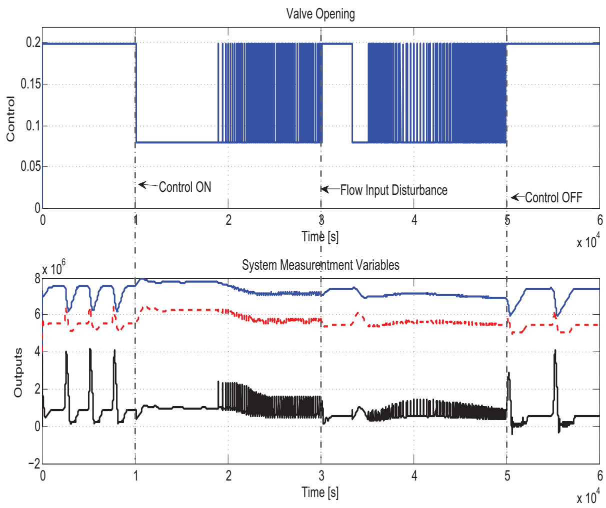

Fig. 12. Control and output system responses with slug washout SMC for a disturbance in the input riser flow rate.

13. As can be seen, the propose control law stabilize the process and at the same time allow to work over the full choke range. A disadvantage to use this propose control law is the resulting

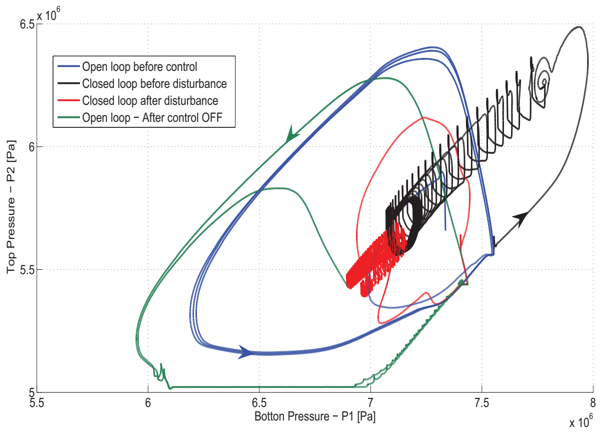

Fig. 13. State-space diagram of the system with slug washout SMC.

chattering produced by the control action signal on the choke. An alternative to overcome the high frequency chattering from the dynamics of the standard sliding mode control presented in the this Section is to design a Higher Order Sliding Mode (HOSM) control.

6. CONCLUSIONS

The lack of robustness to control slug-flow oscillations in submarine oil-risers using classical PI linear control system was tackled in this paper applying SMC techniques. Three different SMC controllers to suppress slug-flow control oscillations were proposed. Simulation results were obtained using OLGA software in order to compare the different SMC strategies subject to mass flow input riser disturbances from $5Kg.s^{-1}$ to $3Kg.s^{-1}$. The SMC technique reveal itself as a robust way of suppressing limit cycles when the mathematical model of the process is not available in practice. The dynamical of the slug system with unknown operating point was treated in this work using washout filters. This situation is manifested in the presence of mass flow rate input riser disturbances.

An existing practical obstacle to apply the standard SMC in the field is the high frequency chattering of the generated control signal. This problem leads to a premature wear down of the choke actuator and could be tackled in future works using High Order Sliding Mode - HOSM controllers.

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