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New Developments in the Control of Fluid Dynamics of wells and risers in oil production systems ⋆

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Abstract: A practical control algorithm for stabilizing flow in risers and oil production wells should meet several requirements. i) be simple, ii) able to operate with low-cost measurements and possibly contaminated with noise and iii) stabilize the flow without setting a value for the bottom pressure. An algorithm has been proposed which does not fix any reference for the bottom pressure. It uses as reference a value equal to zero for the derivative of the bottom pressure. This paper presents some changes in the algorithm in order to avoid the difficulties with derivatives and to simplify the tuning of its parameters. It also proposes a control methodology to suppress oscillations in the absence of automated production choke and downhole measurements.

Keywords: Fluid dynamics, well control, riser control, gas-lift, well simulation.

1. INTRODUCTION

Fluid flow rate oscillations are known as source of problems in oil production systems. The primary fluid treatment process including oil-water-gas separation and gas compression is strongly affected. In extreme cases part of the produced gas has to be directed to the flare and the quality of the separated water and oil is compromised. Besides, production risers may suffer with the fluid acceleration resulting in premature mechanical fatigue. It is also worth mentioning the production loss resulting from the intermittent flow when compared to a stabilized one. The efforts to deal with the problem can be divided in reactive and active control. Reactive control is the name used to describe those systems designed on the assumption that the risers and wells do develop some kind of oscillatory flow-rate. The reactive control system is designed to enable the operation of the primary fluid processing system even with the existence of oscillatory flow behavior. The active control system, on the other hand, acts to eliminate or decrease the flow-rate oscillations delivered by wells and risers. The low number of applications of active control can be attributed to

- lack of instrumentation for measuring and actuation,
- lack of thrust on the control algorithm robustness,
- difficulty on choosing set points,
- conservatism.

Several control algorithms have been proposed to the control of the fluid flow dynamics of wells and risers, F. Di Meglio and Alstad (2012), Sinegre (2006), Meglio et al. (2012), Jahanshahi et al. (2012),Ogazi et al. (2009), Storkaas and Skogestad (2007), Godhavn et al. (2005), Siahaan et al. (2005), Eikrem et al. (2008). Unfortunately there is no space to make a proper review. In Plucenio et al. (2012) an algorithm has been proposed which does not fix any reference for the process variables. It uses as reference a value equal to zero for the derivative of the bottom pressure. The control algorithm has been applied with success in simulations and real wells. This paper presents some advances in well and risers active control including changes in the proposed algorithm in order to avoid the difficulties with derivatives and simplify the tuning of its parameters. This paper is organized as follows: In section 2 the new algorithm is discussed. In section 3 some simulation results are presented. In section 4 a solution is proposed for the case when neither downhole measurement nor active production choke is available. Section 5 concludes the paper.

2. DERIVATION OF THE NEW CONTROL LAW

As explained in Plucenio et al. (2012) the algorithm is based on the equation (1) presented in Sinegre (2006) which derives a relationship between the gas mas fraction x in time t and space z assuming an average gas velocity V_g. Applying Laplace Transform to equation (1) it becomes evident that the gas mass fraction at a position z_2 on the tubing is equal to the gas mass fraction at position z_1, with $z_2 > z_1$ at a time $t - \tau$ with $\tau = \frac{z_2 - z_1}{V_g}$.

$$\frac{\partial x}{\partial t} + V_g \frac{\partial x}{\partial z} = 0 \tag{1}$$

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This result is used on the control strategy by assuming that if the gas mass fraction is stabilized at $z = z_1$ then, provided no other action happens to disturb the flow, the gas mass fraction will remain stabilized at $z = z_2$. Down-hole measurements are scarce but new wells are being equipped with permanent down-hole gauges that measure pressure and temperature. Is there other process variable that when stabilized induces the stabilization of the gas mass fraction? In the sequence it is shown that assuming certain flow conditions, stabilizing the pressure in a position of a flowing pipe also stabilizes the gas mass fraction at that position.

Theorem 1. Stabilizing the bottom pressure in a gas-liquid flow stabilizes the gas mass fraction.

Proof. Consider the pressure difference between the bottom $p(z + \Delta z, t)$ and top $p(z, t)$ of a short pipe section of length Δz with inclination $\theta > 0$ with the horizontal axis where a gas-liquid flow takes place. It is assumed that the top pressure is a constant pressure boundary and there is no mass exchange between the liquid and gas phase. Disregarding the pressure drop due to friction and considering the void fraction $\alpha(t)$ and gas density $\rho_g(t)$ not varying along Δz, the pressure drop can be written as

$$p(z + \Delta z) = p(z, t) + (\alpha(t)\rho_g(t) + (1 - \alpha(t))\rho_l)\, g\Delta z sin(\theta). \quad (2)$$

The density of the gas is

$$\rho_g(t) = \frac{(p(z + \Delta z, t) + p(z, t))}{2}\phi, \text{ with } \phi = \frac{M}{ZRT} \text{ and} \quad (3)$$

$$\begin{aligned} p(z + \Delta z, t) = p(z, t) + \alpha(t)\frac{(p(z + \Delta z, t) + p(z, t))}{2}\phi g\Delta L sin(\theta) \\ -\alpha(t)\rho_l g\Delta L sin(\theta) + \rho_l g\Delta z sin(\theta). \end{aligned} \quad (4)$$

The time derivative of equation (4) is

$$\begin{aligned} \frac{\partial p(z + \Delta z, t)}{\partial t} = \frac{\partial \alpha(t)}{\partial t}\left(\frac{(p(z + \Delta z, t) + p(z, t))}{2}\phi - \rho_l\right) g\Delta L sin(\theta) \\ + \frac{\partial p(z + \Delta z, t)}{\partial t}\frac{\phi}{2}\alpha(t) g\Delta L sin(\theta). \end{aligned} \quad (5)$$

In order to have $\frac{\partial p(z+\Delta z,t)}{\partial t}$ equal to zero it becomes necessary to have $\frac{\partial \alpha(t)}{\partial t} = 0$ or $\left(\frac{(p(z+\Delta z,t)+p(z,t))}{2}\phi - \rho_l\right) = 0$. This last alternative means a gas density equal to the liquid density and will be disregarded. That is, $\frac{\partial p(z+\Delta z,t)}{\partial t} = 0$ implies in $\frac{\partial \alpha(t)}{\partial t} = 0$. But,

$$x(z + \Delta z, t) = \frac{\alpha(t)\rho_g(t)}{\alpha(t)\rho_g(t) + (1 - \alpha(t))\rho_l}, \text{ or} \quad (6)$$

$$x(z + \Delta z, t) = \frac{\alpha(t)\,(0.5p(z + \Delta z, t) + 0.5p(z, t))\,\phi}{\alpha(t)\,(0.5p(z + \Delta z, t) + 0.5p(z, t))\,\phi + (1 - \alpha(t))\rho_l}.$$

Then, if $\frac{\partial p(z+\Delta z,t)}{\partial t} = 0$ implies in $\frac{\partial \alpha(t)}{\partial t} = 0$, using equation (7) shows that it also implies in

$$\frac{\partial x(z + \Delta z, t)}{\partial t} = 0. \quad (7)$$

. □

To avoid the time derivative used in the previous algorithm, Plucenio et al. (2012) a new approach is proposed. The bottom pressure is again assumed to be composed of a mean value and a zero mean value,

$$p_b(t) = \overline{p} + \widetilde{p}_b(t). \quad (8)$$

A wash-out filter is used to obtain $\widetilde{p}_b(t)$, Hassouneh et al. (2004), Colling and Barbi (2001). Assume the following low pass filter in s to obtain the auxiliary variable $v(s)$ with a frequency cut w_c:

$$\begin{aligned} v(s) &= F(s)p_b(s) \\ F(s) &= \frac{w_c}{s + w_c} = \frac{1}{\frac{s}{w_c} + 1} \end{aligned} \quad (9)$$

The following discrete version of the filter can be obtained computing the discrete pole

$$z^* = 1 - d = e^{-w_c T_s}. \quad (10)$$

The equivalent difference equation can be written to obtain the discrete version of the zero mean pressure $\tilde{p}_b(k)$

$$\begin{aligned} v(k + 1) &= dp_b(k) + (1 - d)v(k), \\ \tilde{p}_b(k) &= p_b(k) - v(k). \end{aligned} \quad (11)$$

Starting with $\tilde{p}_b = 0$, there is a change in the riser or wellhead pressure, Δp_h that induces an oscillatory behavior in $\tilde{p}_b$. If the well or riser head is connected to a separator through a choke and a short flow-line,

$$p_h(t) = p_{sep} + p_{ch}(t) \text{ and } \Delta p_h = \Delta p_{ch}. \text{ Thus,} \quad (12)$$

$$\tilde{p}_b(s) = H(s)\Delta p_{ch}(s), \text{ and } H(s) = \frac{Aw_o}{s^2 + w_o^2}. \quad (13)$$

The constant A was inserted to allow for a better tuning of the controller parameters. The angular frequency of the downhole oscillatory pressure can be computed from the period T_o using the time normalized to T_s,

$$w_o = \frac{2pi}{T_o/T_s}. \quad (14)$$

Using a simplified relation between z and s,

$$\begin{aligned} H(z) &= \frac{Aw_o}{(z - 1) - (1 - z^{-1}) + w_o^2} \\ H(z) &= \frac{Aw_o z^{-1}}{1 - (2 - w_o^2)z^{-1} + z^{-2}} \end{aligned} \quad (15)$$

The Z transform shown in equation (15) is an approximation to the exact expression

$$H(z) = \frac{Asin(w_o)z^{-1}}{1 - 2cos(w_0)z^{-1} + z^{-2}} \quad (16)$$

for small w_0 with $sin(w_0)$ and $cos(w_0)$ respectively approximated to first and second order Taylor expansion around zero .

$$\begin{aligned} \Delta p_{ch}(k) = \frac{1}{Aw_o}\tilde{p}_b(k + 1) - \frac{(2 - w_o^2)}{Aw_o}\tilde{p}_b(k) \\ + \frac{1}{Aw_o}\tilde{p}_b(k - 1). \end{aligned} \quad (17)$$

Defining a set-point for $\widetilde{p}_b$ equal to zero, the error $e(k)$ can be written as

$$e(k) = 0 - \widetilde{p}_b(k). \quad (18)$$