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Sliding Control Applied to Subsea Oil and Gas Separation System under Fluid Transient Effects

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Abstract: Liquid level control inside a subsea gas-liquid separator like VASPS, can be a difficult task. Nonlinearities of the dynamical system combined with disturbances on pipelines flow can result on randomness on liquid level behavior. The control approach chosen for the present study was a robust control generally applied to systems where parts of the dynamics are not well known. The Sliding Control despite of its reliability, induces discontinuities in the system that could be harmful to actuator, an ESP pump for VASPS case. Some adaptations were introduced in order to circumvent this problem. An imprecise system model using fluid transient theory was considered and numerically evaluated by method of characteristics. The present paper purposes a controller robust enough to keep the liquid level between specified limits, track a trajectory to be followed by level values along time and, additionally, able to avoid actuator overwork.

Keywords: Sliding Control, Subsea Separation, Fluid Transient, Method of Characteristics, VASPS.

1. INTRODUCTION

Gas –liquid separation applied by the oil industry over the last decades has been mostly based on gravity driven process. These kind of process are specially costly for offshore operations once it requires large and weighty vessel to be installed on the surface platform. As an alternative, it has been developed cyclone-concept separators wich are characterized by compactness, simplicity with no moving parts, low weight and reduced cost. Some of the well known processes are the Vertical Annular Separation and Pump System (VASPS), the Gas-Liquid Cylindrical Cyclone (GLCC) and the Cyclone Separator (CS). (Rosa, F.A., & Ribeiro, 2001).

VASPS, used as reference separator for this paper, is an UK patent application issued to British Petroleum in 1988 and designed for gas-liquid subsea separation. (Rosa, F.A., & Ribeiro, 2001). It consists of a vertical separator that receives multiphase fluid from the well in an intake chamber. The chamber is connected to liquid reservoir pool throughout a no moving helix. At the bottom of the assembly it is installed an Electrical Submersible Pump (ESP) used to raise the fluid to the platform. The separator has two separate pipelines: one for gas and other for liquid. The intake of the device is directly connected to the wellhead or to a manifold system, which receives the production from several wells. The separator is installed on the sea floor. (Melo, Mendes, & Serapião, 2007). An illustration of subsea production facility using VASPS is shown in Fig. 1.

The VASPS concept is often composed of three separation stages. The primary separator is an expansion chamber connected to an inlet nozzle that imparts momentum to the multiphase fluid and discharges it over a cylindrical wall along a tangential direction. The secondary separator is composed of a helix channel in which the mixture flows downward.

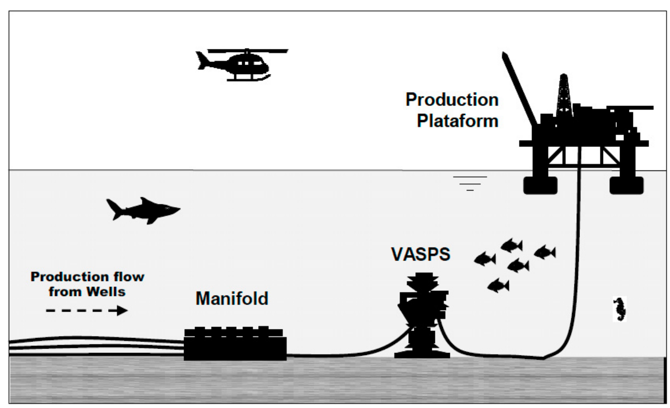

Fig. 1. Subsea production facilities. *(Melo, Mendes, & Serapião, Intelligent Supervision Control For the VASPS Separator, 2007)*

A tertiary separation stage is placed at the bottom of the separator and driven by gravity. At this stage the remaining bubbles dispersed in liquid film that reach the liquid reservoir are expected to be separated by gravitational action once the liquid stays enough time in the pool. (Rosa, F.A., & Ribeiro, 2001)

1.1 System Control

According to Pinheiro et. al. (2011), the control problem consists in maintain the liquid level inside an operational range by choosing the appropriated pump outflow. Out of the referred range two main troubles may occur. If the liquid level surpasses the maximum level specified, the useful area of conducting helix for the secondary separation stage will be reduced. This will lead to a decrease in separation efficiency. On the other hand, if the liquid level gets smaller then a

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specified minimum, a quantity of gas may pass through the pump causing serious damages. An important concern about gas-liquid separation control regards to its lifetime. As the system is installed in fake hole on the seabed any maintenance intervention would be costly. Any designed controller must take in account that the less the number of changes in command speed of the pump, the more its durability may be prolonged.

Difficulties in keeping specified range level arises from the fact that the system shows a nonlinear behaviour. The level inside the separator is a function of the inflow, which is generally present as slug regime, and a function of the gas pressure inside the separator which tends to change the liquid level in a hard to preview manner. Mello et. al. (2007), states that the disturbances caused by slug inflow allied to nonlinearities of the system may imply high randomness, what implies in a hard to predict control actions in order to maintain the desirable liquid level. Addressing the control issue, some different strategies can be found in specialized literature. Melo et al (2007), discussed an 'intelligent supervision control for VASPS separator'. Pinheiro et. al. (2009), adopted a stochastic intervention strategy in which the control was transformed in a sequence of iterated optimal stopping problems and then expresses it as a sequence of vibrational inequalities.

The present paper adopted a control approach using Sliding Control concept introduced by Slotine and Li (1991). The main benefit expected is to reach a reliable controller which can track a desirable curve set to get an optimal relation between actuator effort and level control. Sliding controllers can respond satisfactorily even when parts of the dynamical system are not well known. This can be very useful once it allows to simply disregard a huge part of the system dynamics simply knowing its values limits. Despite of the benefit of dealing with models uncertainties, the controller will have a discontinuous behaviour. Therefore, some adaptation had to be done in order to prevent abrupt changes in pump rotation speed and prolong its lifetime.

2. TRANSIENT FLUID THEORY FOR SYSTEM MODEL

Some simplified models have been used to describe the subsea gas liquid separator behaviour. Melo et al (2009), assumes a third order polynomial which is a pump rotational frequency function. The level time rate is given by the difference between separator inflow and outflow. Shiguemoto et al (2011) take an approach that considers transient fluid effects often present in real case. For its approach, two sets of differential equations presented by Wylie and Streeter (1978) are used, one to describe the liquid flow dynamics in liquid pipeline and another to describe the gas flow dynamics when it is being transported to the platform through its own pipeline. This modelling approach will be used for the present paper with slight differences. The model describes the liquid level inside separator as a function of piezometric head and outflow along liquid pipeline length and over the time. Additionally, the model incorporates changes in level made by gas pressure above the liquid column, where gas pressure is given in terms of mass rate flow and pressure along gas pipeline length and over the time.

For description of the system the equation of motion is derived for liquid flow through a cylindrical tube and is expressed in terms of the centreline of the pressure which is converted to *piezometric head* $H(x,t)$ and outflow $Q(x,t)$, where t and x are, respectively, time and position independent variables. Continuity Equation is written in terms of $H(x,t)$, $Q(x,t)$ and a value a that represents the speed of a sonic wave pulse of high pressure traveling upstream the pipeline at a sufficient pressure to apply just an impulse that brings the fluid to the rest. Motion equation and Continuity equations are shown in (1) and (2), respectively

$$g\frac{\partial H}{\partial x} + \frac{Q}{A^2}\frac{\partial Q}{\partial x} + \frac{1}{A}\frac{\partial Q}{\partial x} + \frac{fQ|Q|}{2DA^2} = 0 \quad (1)$$

$$Q\frac{\partial H}{\partial x} + A\frac{\partial H}{\partial t} - Q\sin\theta + \frac{a^2}{g}\frac{\partial Q}{\partial x} = 0 \quad (2)$$

In above equations A is cross sectional area of liquid pipe, f is Darcy-Weisbach friction factor, g is the gravitational acceleration and θ is the inclination of the pipe with respect to horizontal line, considering that the liquid has no transverse motion in its interior. The pulse wave speed is a quantity that depends on the bulk modulus of the fluid elasticity (K), the Young's elasticity modulus of the pipeline (E), pipeline thickness (e), the liquid density (ρ), a constant function of the Poisson Module of pipe material and diameter of the pipe (D). The wave speed value may be found using (3).

$$a = \sqrt{\frac{K/\rho}{1 + (K/E)(D/e)C}} \quad (3)$$

The equation of motion had the forces acting over the fluid like pressure, friction and gravity forces equated to inertial forces. Although, inertial forces are less important than pressure and friction. Gas flow is subjected to transient effects of long and rapid duration, then equation of motion are adapted by the introduction of an inertial multiplier (α) in order to have an accurate numerical solution. For continuity equation, the formulation of the mass inflow in a short segment of the pipe is equalled to the time rate of increase of mass within this pipe segment. Both, motion and continuity uses state equation of natural gas (4). The equation of the state of the gas is

$$p = z\rho_G RT \quad (4)$$

Pressure (p) is given in terms of gas compressibility (z) which is considered constant during the time of solution, the gas mass density (ρ_G), the gas constant (R) and temperature (T). It is also assumed that during evaluation of the gas flow, the temperature is constant. The acoustic wave speed is written as in (5)

$$B = \sqrt{\frac{p}{\rho_G}} = \sqrt{zRT} \quad (5)$$

Continuity and motion equations for gas flow are presented in terms of the cross-sectional area of gas pipe (A), friction factor (f) and mass rate of flow (M) and gas pressure (p) along the pipe's distance (x) and time (t). Continuity and motion equations are shown in (6) and (7), respectively