BAND CONTROL: CONCEPTS AND APPLICATION IN DAMPENING OSCILLATIONS OF FEED OF PETROLEUM PRODUCTION UNITS

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Abstract: The use of accumulation vessels – production separators, electrostatic treaters, etc – as filters of feed oscillations has been proposed to optimize the offshore treatment of crude oils. This change in philosophy of control suggests letting the level to oscillate within certain limits – called band – for which existing algorithms require the measurement of the flow rate. An alternative algorithm is presented in this paper that requires only the measurement of the level. The basic concepts of the proposal are presented. It is demonstrated that besides being simpler, this algorithm has a superior performance when compared to those that require the measurement of the outflow.

Keywords: Level control, load regulation, stabilization, PI controllers, surge tank.

1. INTRODUCTION

First of a series of separation equipment in petroleum production plants, gravity separators are used for two and three phase separation of gas, oil and water. It feeds dedicated treatment systems designed to specify each of these streams for exportation. In offshore units the inflow of separators is oscillatory, frequently characterized by slugs of liquid and gas coming from the wells, a flow regime generically named slug flow (Shinskey, 1996; Skogestad, 2003). Proportional and integral, PI, controllers are used for level and pressure control. Precise load regulation is adopted to avoid upsets such as liquid carry over, gas carry under, etc. As the integral mode guarantees offset free response for the controlled variables - level and pressure - flow perturbations are not filtered and oscillations are passed to the downstream treatment systems. In general oscillations are minor and this is no cause of concern (Luyben, 1990).

However, flow conditions in platforms, offshore Brazil, are becoming more stringent and higher amplitude slugs have achieved frequencies that result in significant degradation of performance of such plants. Furthermore, in a move to reduce dimensions of offshore platforms, very compact equipment are increasingly more used for water and oil treatment.Their reduced volume makes them especially sensitive to oscillations (Nunes, 2004).

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Thus, an algorithm that is able to dampen the oscillatory feed of gravity separators is desirable. The aim is to keep the manipulated flow as constant as possible, while maintaining the level (or pressure) within bounds. A variety of such proposals is found in the literature: non-linear control, feedforward, proportional control, etc, which are presented under many different names: surge control, level averaging control, etc. However, from an operational point of view most of these applications have serious drawbacks: some require extra measurements (i.e., flow rate), others are hard to tune, and some allow excessive volume change (Cheug and Luyben, 1979).

With that in mind, an algorithm named Band Control has been developed by Petrobras. Its conception is simple and no extra measurement is required beyond that of the controlled variable. The concept applies to any accumulating vessel.

2. TRADITIONAL PI LEVEL CONTROL

Consider the material balance of liquids in separators. For a vessel with length C and diameter D, and assuming linear relationship between the height h and the volume, in which case volume is CDh, then (Nunes, 2004):

$$CD\frac{dh}{dt} = Q_{in} - Q_{out} \quad (1)$$

where Q_{in} is the inflow volumetric flow rate and Q_{out} is the outflow volumetric flow rate. The outflow can be described by a simple equation of the valve:

$$Q_{out} = u\ C_V\sqrt{\Delta P} \quad (2)$$

where u is the control action, C_V is the flow rate coefficient and ΔP is the pressure drop in the valve. Consider further that the dynamics of the valve is much faster when compared to the other components of the system. This means that the control action, u, is similar to the opening of the valve. The material balance becomes

$$CD\frac{dh}{dt} = Q_{in} - uC_V\sqrt{\Delta P} \quad (3)$$

$$h(s) = \frac{1}{CDs}\left(Q_{in}(s) - C_V\sqrt{\Delta P}\ u(s)\right) \quad (4)$$

PI controllers are normally used in the level control, and the transfer function is (Åström *et al.*, 1994)

$$u(s) = \overline{K}_c\left(1 + \frac{1}{s\overline{T}_I}\right)(hr(s) - h(s)) \quad (5)$$

where $hr(s)$ corresponds to the reference or setpoint, $\overline{K}_c$ e $\overline{T}_I$ are parameters of the PI. The block diagram and the PI control structure of a gravity surge tank separator are given in Figures (1) and (2), respectively (Skogestad, 2003; Wu *et al.*, 2001).

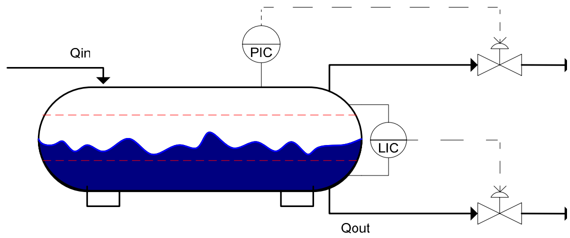

Fig. 1. Diagram of a gravity surge tank separator.

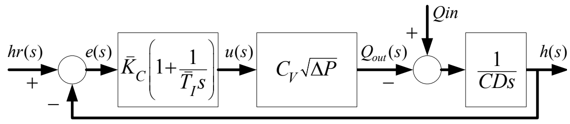

Fig. 2. PI control of a gravity surge tank separator.

3. LEVEL CONTROL WITH LOAD ESTIMATION

One of the many possible ways to use gravity separators for the dampening of inflow, the application that uses the measurement of outflow to infer the inflow will be analyzed. Consider the level control of a separator as in Figure (2). If the controlled variable is kept as close as possible to the setpoint then an increase of inflow results in a similar increase in outflow. Thus, no filtering is done. Conversely if the level is allowed to oscillate then the outflow is more constant. However, there are maximum and minimum limits allowed to the level, which depend on many factors, such as the chemical nature of the crude, type of downstream equipment, etc. For the condition when the level is out of bounds the algorithm has to aggressively bring it back to the interior of the band. Some algorithms use variable proportional action, some use gain scheduling, other switched to a fast PI. We will focus the analysis on the control within the band. To promote the filtering capacity desired, the outflow should be the average inflow while the level is allowed to oscillate inside these limits, or band. For that an estimate of the inflow is necessary, which can, theoretically, be inferred from the material balance of the vessel. The drawbacks to this approach will be discussed hereon.

3.1 Conventional Controller Design.

The problem of dampening the inflow of vessels without restrictions on the level (Friedman, 1994)

$$CD\frac{dh}{dt} = Q_{in} - Q_{out} \quad (6)$$

has a trivial solution: Q_{out} = ‹Q_{in}›. The outflow should be the time average of the inflow. The inflow can be inferred from the measurements of the outflow and the derivative of the level.

$$\hat{Q}_{in} = Q_{out} + CD\frac{dh}{dt} \quad (7)$$

The time average should be calculated along the period T of the perturbation, which needs to be known or estimated (Qui-Huu, 1998). This means that

$$Q_{out} = \left\langle \hat{Q}_{in} \right\rangle = \frac{1}{T} \int_{t-T}^{t} \hat{Q}_{in}\, dt \qquad (8)$$

So, the control law is

$$Q_{out} = \frac{1}{T} \int_{t-T}^{t} \left(Q_{out} + CD \frac{dh}{dt} \right) dt \qquad (9)$$

This control law indicates the value Q_{out} should be, based on measurements of Q_{out} itself and h. Its implementation can be done using an outflow controller, FIC, whose setpoint is the calculated value of Q_{out}, a cascade control. However, the use of this equation should be avoided first because calculating derivatives amplifies errors and as a consequence filters become necessary. Furthermore, obtaining the time average of derivatives is a waste of efforts as it results in the difference between the actual and past values of the level, a much simpler numerical procedure. Still, other drawbacks can be shown to this control law. To further investigate this apply Laplace to equation (9) to get

$$Q_{out}(s) = \frac{1-e^{-Ts}}{Ts} Q_{out}(s) + \frac{CD}{T}(1-e^{-Ts})h(s) \qquad (10)$$

Based on the material balance the transfer functions are obtained as follows:

$$\frac{Q_{out}(s)}{Q_{in}(s)} = \frac{1-e^{-Ts}}{Ts} \qquad (11)$$

$$\frac{h(s)}{Q_{in}(s)} = \frac{Ts - 1 + e^{-Ts}}{CDTs^2} \qquad (12)$$

The frequency analysis shows that dampening of sinusoidal waves is done correctly; i.e., Q_{out} is constant, as long as T corresponds to the exact period of the wave. However, no clear period can be defined for slug flow. As a consequence, after the passage of a slug, the final value of the level may be located anywhere inside the separator (e.g., very close to the limits of the band) which is undesired. This behavior is a direct consequence of the term $(1 - e^{-Ts})h(s)$.

As no restrictions were imposed during the development of the mathematical problem to allow for the regulation of the level this algorithm has rigorously speaking only one tuning parameter T, related to the frequency of the inflow. From a practical point of view it lacks a tuning mechanism able to change the strength of the filter. To get around this disadvantage a proportional and integral controller, LC, is necessary (Kothare *et al.*, 2000). The block diagram of such implementation is seen in Figure (3). Note that the LC will compete with the term $(1-e^{-Ts})h(s)$ and tuning is a difficult task. Finally, this implementation has 5 tuning parameters: 2 for the LC, 2 for the FIC and T, as shown in Figure (3).

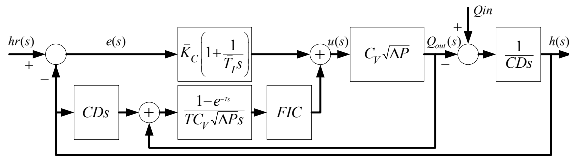

Fig. 3. Level control with smoothness of the outflow.

This algorithm has been reportedly implemented in Filho (2004).

3.2 Band Controller Design.

A simpler and more robust controller can be derived from the same initial control law, equation (10). Consider the equation of the valve $Q_{out}(s) = u(s) C_V \sqrt{\Delta P}$, which relates its opening to the outflow. Substituting it in equation (10) we get a control law that is independent of flow measurements. Furthermore, we suggest substituting the second term (whose origin comes from an attempt to correctly predict the inflow by adding to the outflow the contribution of volume change) by a proportional controller which is, from a practical point of view, another way to correct the differences between Q_{out} and Q_{in}.

The control law becomes

$$u(s) = \frac{(1-e^{-Ts})}{Ts} u(s) \ \ + K\, e(s) \qquad (13)$$

$$u(s) = \frac{KTs}{Ts - 1 + e^{-Ts}} e(s) \qquad (14)$$

where $e(s) = hr(s) - h(s)$, k^* is a fine tuning parameter and

$$K = \frac{-k^* CD}{TCv\sqrt{\Delta P}}$$

This way K is the tuning parameter lacking. A higher value of K makes this controller a stronger regulator. The offset caused by a proportional control is irrelevant first because it is small and also because we are dealing with a system subject to a variable feed for which no steady state is foreseen. The block diagram of this controller is shown in Figure (4).

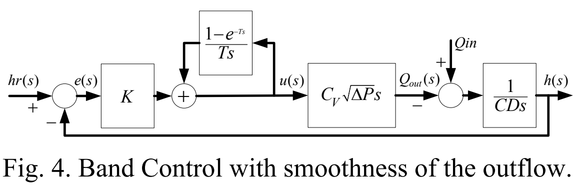

Fig. 4. Band Control with smoothness of the outflow.

For the specific application of level control it has been named Level Band Control. The closed-loop transfer functions are

$$\frac{u(s)}{Q_{in}(s)} = \frac{-KT}{CD(Ts - 1 + e^{-Ts}) - KTCv\sqrt{\Delta P}} \quad (15)$$

$$\frac{h(s)}{Q_{in}(s)} = \frac{Ts - 1 + e^{-Ts}}{CDs(Ts - 1 + e^{-Ts}) - KTCv\sqrt{\Delta P}s} \quad (16)$$

Note that K allows the change of poles of the system. Although this controller has only two tuning parameters, T and K, its project is more consistent with the original purpose of filtering slug flow in gravity separators.

3.3 Comparative Block Diagrams.

An intuitive way to compare algorithms is through the use of block diagrams. Suppose excellent performance of the flow controller, guaranteeing exact regulation. In this case its transfer function can be approximated by $1/C_V(\sqrt{\Delta P})$. This way the block diagram of Figure (3) can be recast into the one seen in Figure (5).

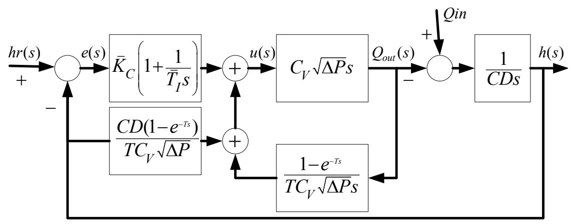

Fig. 5. Level control with smoothness of the outflow.

Rearranging once again we get Figure (6).

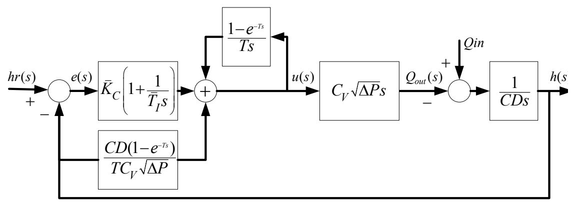

Fig. 6. Level control with smoothness of the outflow.

Remembering that as has been shown, the average value of the derivatives is the difference in values of the level, and after cancellation of common terms we then get Figure (6). Compare it to the block diagram of the Band Control, Figure (4) to see that the use of the FIC and the calculation of the average value of the derivatives is unnecessary.

3.4 Analogy with PI Controller.

Pade approximation

$$e^{-Ts} \cong \frac{2 - Ts}{2 + Ts} \quad (17)$$

can be used to derive a controller under the mask of a PI structure. Substituting equation (17) in the transfer function of the Band Control, equation (14), then

$$\frac{KTs}{Ts - 1 + e^{-Ts}} \cong K\left(1 + \frac{2}{Ts}\right) = K_c\left(1 + \frac{1}{\tau_I s}\right) \quad (18)$$

a proportional and integral controller is obtained and shown in Figure (7). In this case the integral time τ_I is *T/2*. This approximation gives good results and simplifies significantly the implementation. Bear in mind that the integral term should not be limited (*reset wind-up*) and that the horizon of the integral should correspond to the period *T*.

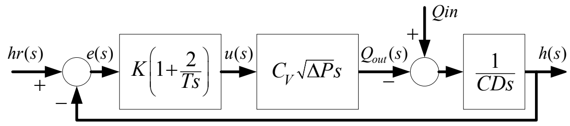

Fig. 7. Level control with smoothness of the outflow.

3.5 Adaptive Band Controller Design.

The Band Control is switched to a fast PID every time the level is outside the limits of the band. In order to avoid using the PID and to make band strategy more robust, an adaptive conception is proposed. The new adaptive term is the gain (K) of the Band Controller, equation (13), that is adapted according some criterion that define when the level is out of limits. Two conceptions are implemented as follows (Ljung, 1999):

Adaptive Gain with Exponential Variation (BAEV): In this conception the gain K is switched for a high value and varying exponentially according the following criterion:

$$K(t) = \begin{cases} -(K_0\left|K(t-1)\right| + [1 - K_0]) \ if \ h_{max} < h < h_{min} \\ K_{ss} \ otherwise \end{cases} \quad (19)$$

where $K_0 < 1$ and K_{ss} are tuned by the operator.

Adaptive Gain with Error Bounded (BAEB): This conception is derived from the covariance resetting technique and the Band Control is given by

$$K(t) = \begin{cases} -\left|\frac{e(t)}{K_0}\right|, \ if \ |e(t)| > e_{max} \\ K_{ss} \quad otherwise \end{cases} \quad (20)$$

The gain K leads for a directly proportional value of error, when the absolute error becomes out the maximum value, e_{max}, defined by the operator as function of the operational level limits. This means that

$$e_{max} \leq min\{\left|h_r - h_{max}\right|, \left|h_r - h_{min}\right|\}$$

4. RESULTS AND DISCUSSIONS

A case study was done on a gravity separator (diameter = 2.8 meters, length = 5.4 meters), of platform P-07 in Campos Basin, offshore Brazil. Data were recorded for period of 12 hours with a sampling time of 6 seconds. Inflow values, Figure (8), were measured from the plant.

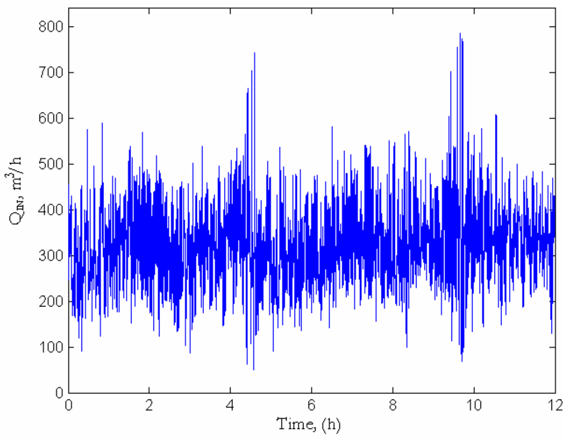

Fig. 8. Inflow behavior of the plant.

Figure (9) presents responses of the plant with the PID controller tuned by operational personnel. Level values show load changes occurring at a period of 2:20 hours. However, outflow values show that higher frequency disturbances are not filtered appropriately. Simulations were done in Matlab to evaluate the performance of the Band Control under the same (field) conditions. Parameters used were:

- Maximum level, h_{max} = 1.6 meters
- Minimum level, h_{min} = 1 meter
- P = 0.67, I = 100 and D = 0
- Period of T (minutes) = 10
- K of the Band Control = 0.48

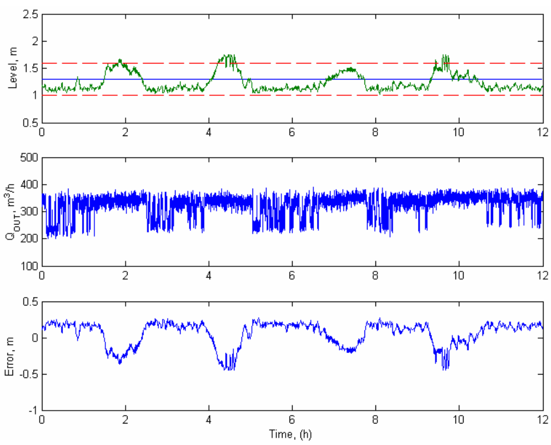

Fig. 9. Level, outflow and error responses for PID controller.

Figures (10) and (11) show the comparison between the existing PID and the Level Band Control. A smaller time period was used, from 5:00 to 6:00 hours. It can be observed that the level fluctuates and the corresponding stabilization of the outflow is achieved using the Level Band Control.

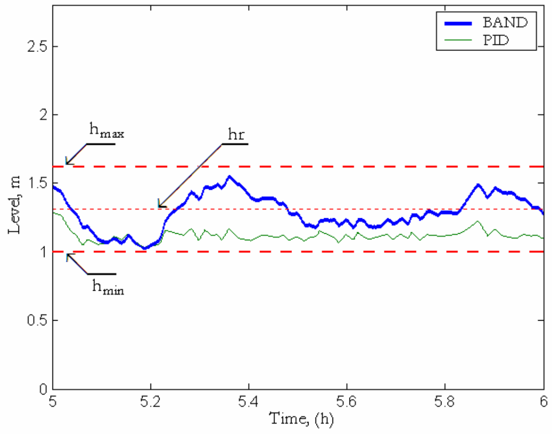

Fig. 10. Level response for band and PID controllers.

Results show that outflow filtering is very good. During most of the time the level is kept within the limits of the band. Note that the limit of the band (between 1.6 and 1 meters) corresponds to a volume of 12.8 m^3. Another band could have been used instead, as long as it corresponds to the same volume.

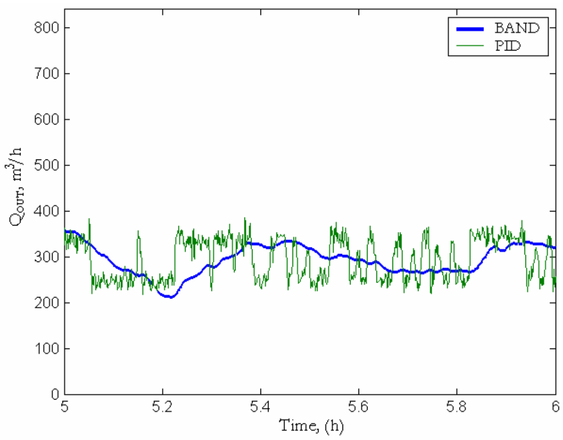

Fig. 11. Outflow response for band and PID controllers.

Next, for comparison purposes, Figure (12) shows the results for the Band Control in nonadaptive and adaptive forms from the beginning until 1:00 hour. Tuning parameters for the adaptive Level Band Controllers, equations (19) and (20), are K_0 = 0.99, K_{ss} = -0.48 and e_{max} = 0.3.

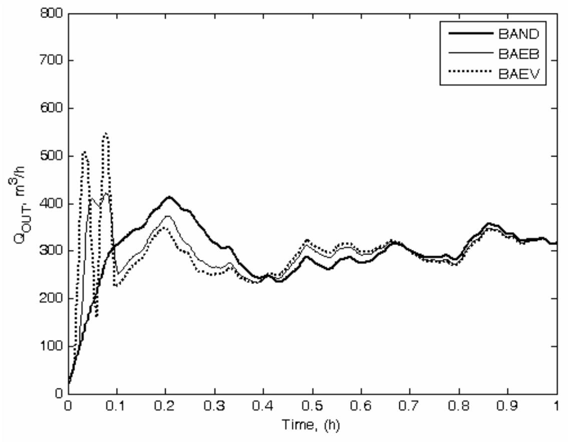

Fig. 12. Outflow response for nonadaptive and adaptive Band Controllers.

Responses indicate small changes on the level and outflow behavior for both Level Band Control strategies, especially at the beginning of the experiment. Away from this time period, both band controllers present the same performance. It is important to keep in mind that:

- The purpose of a surge vessel level control is to dampen the changes in controlled flow while keeping the liquid in the vessel between limits;
- The adaptive Band Control algorithms do not implement a PID when the level is out of the operational limits. So, concerning these two hypotheses the adaptive Band Control algorithms achieve good behavior.

4.1 Benefits of the Band Control.

The following benefits are attributes to the Band Control implementation: simple and easy to implement; does not require the measurement of flow; applicable to all accumulation vessels; applicable to the water, oil and gas phases; promotes stabilization of outflow of separators that improves the performance of all downstream equipment; stabilizes the flow and pressure in the exportation pipeline.

5. CONCLUSION

The use of the material balance for the development of controllers that stabilize the outflow of accumulation vessels has been analyzed. It is shown that the use of derivatives of the controlled variable should be avoided.

A new and simple control algorithm based on the material balance has been presented. It is shown that regardless of its simplicity its performance is superior to similar algorithms. An alternative form is presented for implementation as PID. Field data was used to simulate its use in a gravity separator of a platform. Results show enhanced performance compared to the PID currently used.

Finally, adaptive Level Band Controllers were assessed, BAEV and BAEB, in accumulating vessels, showing also good behavior when compared to the conventional PID controller.

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