CONTROLLING THE PERFORMANCE OF A CYCLONIC OIL-WATER SEPARATION SYSTEM

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Abstract: This work analyzes various configurations for the control of a recently developed compact oil-water separation process for offshore production platforms consisting of a gravity separator and a sequence of three modules of hydrocyclones. Three different control algorithms were compared for interface level control in the separator: proportional and integral, band and linear model predictive control. These algorithms were combined with a classical differential pressure ratio (DPR) control for the modules of hydrocyclones. Results have shown that band control is a promising approach for the interface level and that the DPR control is better if only used in the last module of the sequence of hydrocyclones.

Keywords: Process control, control algorithms, load regulation, level control, process models.

1. INTRODUCTION

In petroleum production plants, gravity separators are used for three-phase separation of gas, oil and water. Its inflow is oscillatory, frequently characterized by slugs of liquid and gas coming from the wells, a flow regime generically named slug flow. 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 an offset free response for the controlled variables - level and pressure - flow perturbations are not filtered and oscillations are propagated to the downstream equipments.

Recently flow conditions in offshore platforms 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 equipments are increasingly more used for water and oil treatment. One such case is the development of a more efficient water treatment system, based on hydrocyclone technology. A sequence of three different types of hydrocyclones, designed for very high oil concentration streams, is being researched. Although the resulting unit is very small its reduced volume makes it extremely sensitive to oscillations. In this case a control algorithm that is able to dampen the outflow of gravity separators should be crucial.

This is known as the problem of level control for surge tanks and has been studied extensively since the 1960s (Buckley, 1964; Shinskey, 1967). The objective is to use the vessels capacity to filter inlet flow disturbances, reducing its propagation to downstream equipments. As level constraints limit the tanks usable inventory, a trade off must be met between filtering capacity and allowable – within bounds - performance. For this purpose innumerous control strategies, from linear to non-linear, have been proposed and analyzed (Cheung and Luyben, 1979 (a), 1979 (b) and 1980; McDonald and McAvoy,

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1986; Campo and Morari, 1989; Friedman, 1999; Bequette, 1998; Nunes, 2005).

Over the last two years Petrobras has implemented what has been named “band control” in the gravity separators of several of its platforms (Nunes, 2005). Its simplicity has attracted operators and helped popularize the algorithm in Petrobras. However its application has been restricted to the level control of two phase (gas-liquid) separators. For the oil-water interface no application has yet been reported.

In this article three different control (PI, band and linear model predictive - MPC) strategies are studied for the control of the oil-water interface level in a separation system made up of a three-phase gravity separator and three modules of hydrocyclones.

2. SYSTEM DESCRIPTION

In offshore production plants, Figure 1, gravity separators, compressors, hydrocyclones (de-oilers) and electrostatic treaters are used to specify oil, gas and water for exportation. Electrostatic treaters execute the de-hydration of oil and hydrocyclones de-oil the water. As no recycling occurs a simple structure of vessels in series results. Although this sequence of accumulation vessels indicate that substantial attenuation of feed can be obtained if proper control is done, fast acting loops designed for disturbance rejection propagate the disturbances of flow rate.

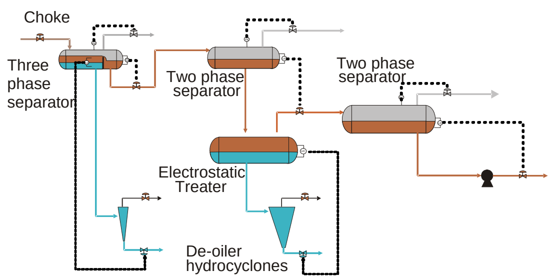

Fig. 1. Offshore process plant

Typically the water discharged by the three phase separator has a concentration of oil of approximately 0.1 % (1000 ppm). Hydrocyclones known as “de-oilers” execute further treatment of such streams reducing the oil concentration to approximately 200 ppm after which it is sent to flotation units for final specification at 20 ppm.

Recently Petrobras has been investigating the use of high oil concentration hydrocyclones in what is expected to be a more compact water treatment system able to debottleneck existing plants by discharging more water from the three phase separators. The proposed configuration, Figure 2, is made up of a sequence of three modules of hydrocyclones able to treat water streams with very high oil concentrations (as much as 30% of oil). The first hydrocyclone, known as BOW (for bulk oil-water cyclone) reduces the oil concentration to approximately 15%. The second is the PDC (pre de-oiler cyclone), which extracts most of the oil in order to specify the water at the 1000 ppm required by the de-oilers. The oily water is then sent to the third cyclone, which is the DC (de-oiler cyclone itself).

Typically hydrocyclones are controlled to maintain a certain ratio of pressure drops (DPR) between the overflow and underflow, which results in a constant ratio of flow rates. This strategy assumes constant oil concentration in the outflow of the separator. This is achieved by adopting a (oil-water interface) level regulator designed for disturbance rejection – a proportional and integral controller with high gain. As a drawback to this approach flow rate disturbances are propagated to the hydrocyclones.

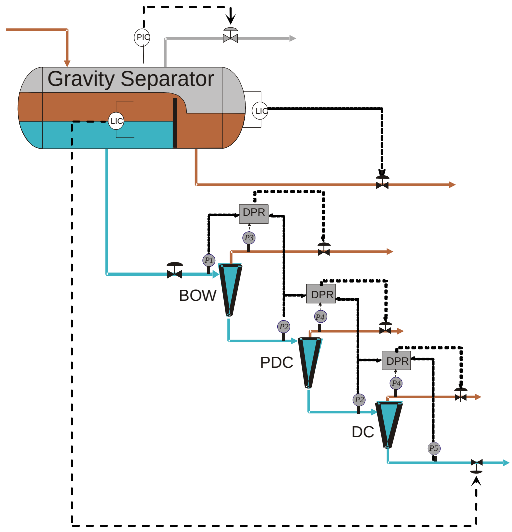

Figure 2 Cyclonic water treatment unit

Thus a good control strategy should try to maintain flowrate and oil concentration both as constant as possible. The ultimate goal is to achieve maximum oil-water separation performance for the whole water treatment system, under periodical oscillations in the feed of the gravity separator.

3. SYSTEM MODELING

The three phase gravity separator is described by a simplified dynamic phenomenological model (Nunes, 2001), based on mass balances in three regions, easily identified in Figure 2: separation chamber, oil chamber and gas space. Dispersed droplets trajectories are calculated and a population balance is done to estimate the oil-water separation efficiency. This model is able to correctly predict the trends in oil-water separation under dynamic changes.

For this investigation it was considered a 5.4m long horizontal cylindrical separator, with a diameter of 1.8m. The separation chamber is 4.4m long and is separated from the oil chamber by a 1m weir. The average values of the liquid (oil and water) and gas feed flow rates were, respectively, 1.962 and 7.8 m^3/min.

Due to negligible residence time ($\approx$ 2s), compared to separators ($\approx$ 600s) hydrocyclones can be considered

in quasi-steady state. They are modeled following a phenomenological approach relating oil separation efficiency with input flow rate and oil concentration (Moraes, 1994, Wolbert et al., 1995). Efficiency is calculated based on the oil droplets trajectories in the system; droplets bellow a certain size leave the hydrocyclones through the underflow.
For the high oil concentration hydrocyclones – BOW and PDC - no phenomenological models, which could be useful for control analysis, have been reported. This is a consequence of the very complex nature of the two-phase (oil and water emulsions) flow. Thus field experiments were executed to generate the required empirical models (Moraes, 2005).

In this work six BOW hydrocyclones were used in the first module, six PDC in the second module and five DC in the last one.

4. CONTROL STRATEGIES AND RESULTS

The main control objective for the system depicted in Figure 2 is to maintain the quality of the water phase leaving the underflow of the DC module, rejecting the negative effect of a periodical slug water flow fed to the separator, shown in Figure 3.

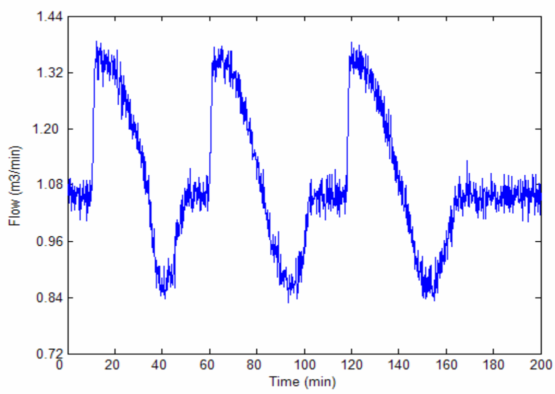

Fig. 3. Periodic input slug water flow

As shown in Figure 2, the controlled variables of the system are the oil-water interface level in the separation chamber, the level in the oil chamber, the separator pressure and the oil concentration in the DC module underflow stream. The manipulated variables are the flow rate of the DC underflow (water phase), the oil outlet flow rate of the separator, the gas outlet flow rate of the separator and the flow rates of the overflow of the hydrocyclones.

Because of one-way interaction a decentralized control scheme was adopted for the separator, with PI controllers for separator pressure and oil chamber level. For these controllers the following tuning was used: oil level, T_I (reset time) = 0.5 min, K_c (proportional gain) = -390 %/m; pressure, T_I = 1,65min, K_c = -24 %/kg$_f$/cm^2. It should be noted that tuning values for all control strategies used in this work were obtained by a trial and error approach.

As already mention, for the interface level in the separation chamber three different control strategies were tried: PI, band and MPC.

The first one was used as a reference, taking into account that it is the most popular approach for surge tank level control (Friedman, 1999).

Band control strategy considers two different control laws depending on the interface level position. When this level is between certain limits of a band, the control action is a combination of two signals, one proportional to the measured error and the other an average of the manipulated variable, in this case inferred from the valve position. The average value is calculated along the period of the slug flow. This control law can be explained as follows.

Due to high operation pressure ($\approx$ 10 kg$_f$/cm^2) the separation chamber behaves almost as a surge tank (an integrator). Consider a simplified model of this system

$$\frac{dy}{dt} = d - u \tag{1}$$

where y represents volume, d the input flow and u the output flow.

For a periodic perturbation a smooth output requires $u = \bar{d}$, where $\bar{d}$ is the average value of the perturbation. Using Equation (1), this value can be inferred from

$$\bar{d} = \bar{u} + \frac{d\bar{y}}{dt} \tag{2}$$

$$\bar{d} = \frac{1}{T}\left[\int_{t-T}^{t} u \cdot d\tau + y(t) - y(t-T)\right] \tag{3}$$

To simplify this approach, and to follow variations of the input average value, it was proposed the following modification (Nunes et al., 2005)

$$\bar{d} = \frac{1}{T}\int_{t-T}^{t} u \cdot d\tau + K(r - y) \tag{4}$$

where r is the reference value for y.

The transfer function of the resulting control law is

$$u(s) = \frac{KTs}{Ts - 1 + e^{-Ts}}[r(s) - y(s)] \tag{5}$$

This control law is similar to the PI, with the advantage that the average operation produces smoothing effect on the control signal.

When the band limits are exceeded a stronger PI control law (K_{cout}, T_{Iout}) takes action to return the level to these limits, and to recover the surge capacity of the separator.

Predictive control (McDonald and McAvoy, l986) was selected because, although more complex than the other two algorithms, it allows a direct weighting of two desired but opposite objectives: constant level - implying in constant composition - and constant output rate flow.

Initially the three modules of hydrocyclones were controlled using a DPR scheme, as shown in Figure 2. This scheme keeps a constant ratio between the two pressure drops: the inlet-overflow, and the inlet-underflow pressure drops. Depending on the oil concentration of the input flow, BOW and PDC hydrocyclones have an ideal DPR value that results in the best separation performance. These ideal values were adaptively inferred using correlations built from field experimental data. For all the simulations the DPR for DC hydrocyclones was fixed at the design value, 2.5. To keep these DPR values at the desired setpoint, PI controllers were used to manipulate the overflow flow rates for any change in the underflow flow rates.

Results obtained when controllers were tuned for the best performance for each separator interface level control strategy, PI, band, and MPC, are presented in Figures 4-6. The tuning parameters are listed in Table 1 in terms of the corresponding control loops: BOW overflow, PDC overflow, DC overflow and DC underflow. Recall that DPR control schemes are based on PI controllers.

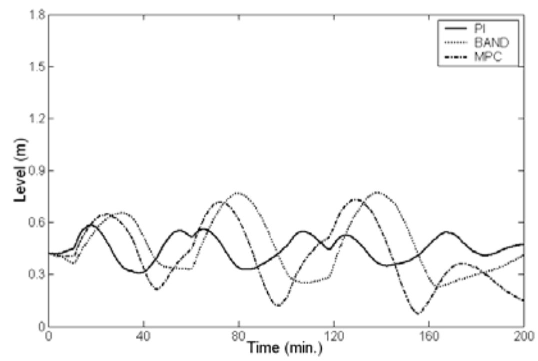

Fig. 4. Oil-water interface level in the separator

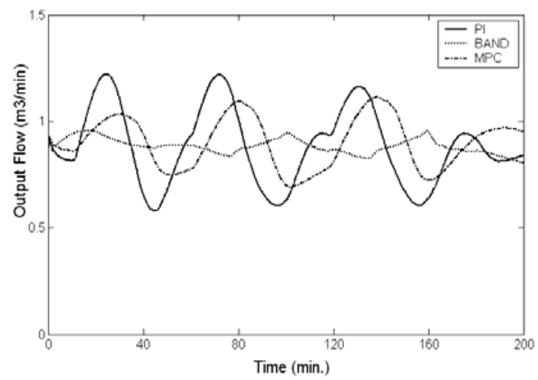

Fig. 5. Water outlet flow rate from the separator

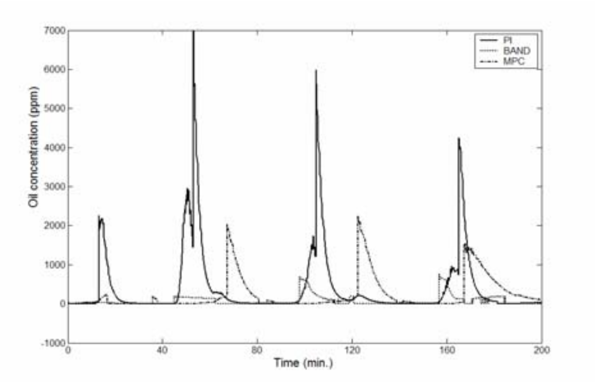

Fig. 6. DC underflow oil concentrations

It can be seen in Figures 4 and 5 that all three controllers manage to maintain the interface level out of the dangerous regions (0.1-0.9m). Although MPC control produces the oscillations of biggest magnitude in the interface level, it was the band control that results in smoother variations of the output flow rate. This is a good result for a surge tank but it should be noted that oscillations of the level produce oscillations of the oil concentration that can modify the separation efficiency of the downstream hydrocyclones.

Figure 6 shows an irregular behavior for the main controlled variable. Again it is clear that the band strategy presents the better performance, but also in this case the system shows significant sensibility to interface level and flow rate variations

The reason for this behavior could be related to the use of DPR control strategies for the three cyclones modules. Although the interface level controller acts directly on the underflow rate flow of the DC module, the DPR strategies indirectly modified the overflow flow rate of each module, not always resulting in a smooth rate flow from the separator.

Table 1 Controllers tuning parameters when using DPR control for all hydrocyclones modules

Loop	PI	Band	MPC
BOW overflow	K_c=3.5 T_I=0.8	4.0 0.8	3.5 0.8
PDC overflow	K_c=4.0 T_I=0.8	1.0 0.8	2.0 0.8
DC overflow	K_c=8.0 T_I=0.8	8.0 0.8	8.0 0.8
DC underflow	K_c=-200 T_I=15	K=-0.2 T=13 K_{cout}=-180 T_{Iout}=50	P=10 M=1 γ=60 λ=30

overflow: K_c[=]%/kg$_f$/cm^2, T_I[=]min; underflow: K_c[=]%/m, T_I[=]min, T[=]min; P: prediction horizon; M: control horizon;γ: controlled variable weight;λ: control variable change weight.

To investigate this behavior a new control configuration was used manipulating the flow rates of the DC module underflow, and the BOW and PDC modules overflows to control the separator interface level. DPR was controlled only for the DC module.

Results of this new strategy can be seen in Figures 7-9, for the same variables of Figures 4-6. The tuning parameters of the controllers for this case are listed in Table 2.

From these figures it can be seen that the new control configuration has produced better results, especially with respect to the main controlled variable, the oil concentration at the DC module underflow. Comparing Figures 6 and 9 it is clear that all three algorithms produce acceptable results for the interface level control, although the band strategy again shows to be slightly better than the other two.

Table 2 Controllers tuning parameters when using DPR control only for DC module

Loop	PI	Band	MPC
BOW	K_c=-10.0	-10.0	-10.0
overflow	T_I=3	4	4
PDC	K_c=-10.0	-10.0	-10.0
overflow	T_I=3	4	4
DC	K_c=6.0	8.0	6.0
overflow	T_I=0.8	0.8	3
DC	K_c=-50.0	K=-0.2	P=10
underflow	T_I=15	T=13	M=1
		K_{cout}=-180.0	γ=80
		T_{Iout}=50	λ=5

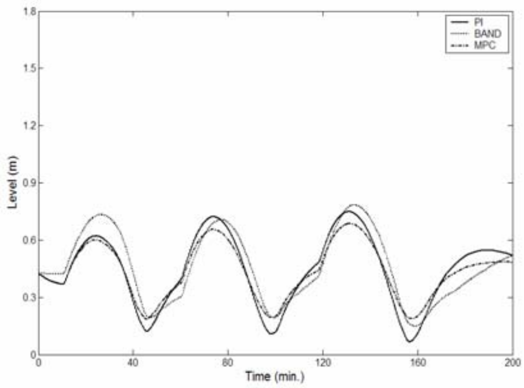

Fig. 7. Interface level without DPR control in BOW and PDC hydrocyclones modules

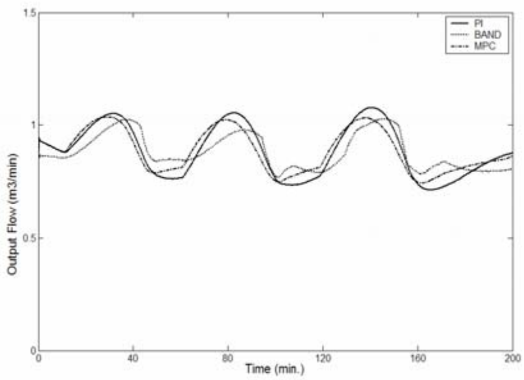

Fig. 8. Output flow rate without DPR control in BOW and PDC hydrocyclones modules

The nice results produced by the new cocntrol configuration are mainly the consequence of a better efficiency in the PDC module. This can be clearly observed comparing results in Figures 10 and 11, representing this efficiency for the original and the new control configurations, respectively. Note the difference of scales in these figures, necessary due to the high regular efficiency in the second case.

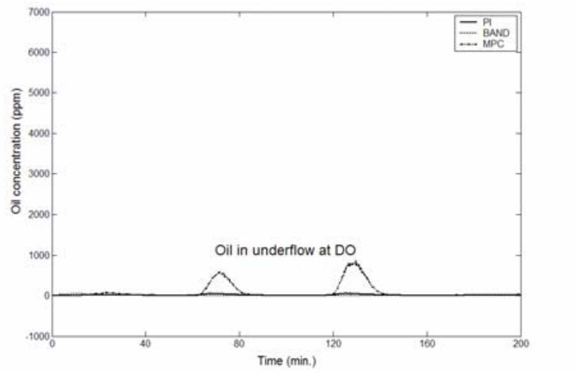

Fig. 9. Oil concentration without DPR control in BOW and PDC hydrocyclones modules

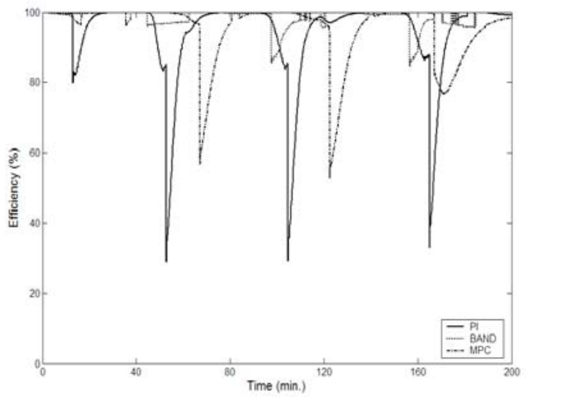

Fig. 10. PDC module efficiency with DPR control in BOW, PDC and DC hydrocyclones modules

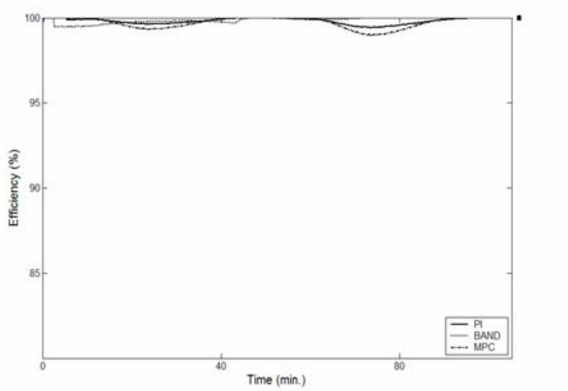

Fig. 11. PDC module efficiency without DPR control in BOW and PDC hydrocyclones modules

5. CONCLUSIONS

This work analyzes some preliminary control aspects of a new configuration for the primary treatment in offshore platforms. Although this configuration will reduce the size of primary treatment units, it presents important operational constraints associated with the fast dynamic behavior of the hydrocyclones. The classical DPR control strategy seems to be of limited use if applied to a sequence of modules of hydrocyclones. When this strategy was applied only to the last module of the sequence the performance of the global system was significantly better than when it was used for all the cyclones modules. Another result of this analysis was that the band controller represents a satisfactory solution for the interface level control problem, especially considering that it is very simple to be implemented in commercial hardware.

We consider that these are preliminary results for the solution of a problem that deserves more investigation, as it is just one part of a more complex system that certainly will require optimization and multivariable control approaches. These problems are nowadays under investigation

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