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Experimental Control of Annulus Pressure While Drilling Oil Wells

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Abstract: Under a conventional oil well drilling task, the pore pressure (minimum limit) and the fracture pressure (maximum limit) define mud density range and pressure operational window. During oil well drilling, several disturbances affect bottom hole pressure; for example, as the length of the well increases, the annulus bottom hole pressure varies for growing hydrostatic pressure levels. In addition, the pipe connection procedure produces disturbances in well fluids flow, changing well pressure. The objective being tracked is operating under desired pressure levels, which assures process safety, also reducing costs, as drilling operation demands around U$500,000.00/day. In this scenario, control techniques are important tools for narrow operational windows, commonly observed at deepwater and pre-salt layer environments. The major objective of this paper is controlling annulus bottom hole pressure of a drilling experimental unit, using the choke opening index as the manipulated variable, in order to guarantee safe operation (target annulus bottom hole pressure), despite the inherent process disturbances and under a scenario that maximization of ROP (rate of penetration) is a target.

Keywords: Constraints, Monitoring, Modeling, Identification, Hydraulic.

1. INTRODUCTION

There are many disturbances that produce fluctuations in the well pressure during oil well drilling. As the well is drilled, the hydrostatic pressure increases because of the well length grow. In addition, the reservoir fluid influx changes the well flow rate and rheological properties of the well fluid mixture. Finally, the pipe connection procedure, which requires stopping and starting of the drill fluid, produce severe fluctuations in the well flow rates.

Despite pressure fluctuations caused by process inherent disturbances, the pressure balance between the well section and the reservoir is an important constraint. If the pressure in the well is higher than the reservoir pressure (over-balanced scenario), the circulation fluids might penetrate into the reservoir. Over-balanced drilling is the most used method for drilling oil wells in Brazil, for it nearly eliminates the risk of an uncontrolled kick situation, named blow-out, where large amounts of the reservoir fluids penetrate into the well and follow the well to the surface. Another scenario is the under-balanced drilling operation, where the pressure in the well is lower than the reservoir pressure, promoting reservoir fluids migration into the well annulus. The use of blow-out preventers assure safe under-balanced drilling conditions, leading to less damage of porous formation, also increasing productivity (Nygaard et al., 2006).

During oil well drilling, the pore pressure (minimum limit) and the fracture pressure (maximum limit) define mud density range. As a result, the drilling fluid hydrostatic pressure needs to be higher than pore pressure, in order to avoid formation fluid invasion into the well. Simultaneously, the drilling fluid hydrostatic pressure needs to be smaller than fracture pressure, for avoiding formation damage.

Concerning the oil well drilling process, its intrinsic nature is distributed and dynamic, because of the increase of the well length, as the well is drilled, and the periodic stopping and starting of the mud pump. In addition, the process can be classified as ranging from an open to closed system, as the choke opening index is varied from 100% to 0%, respectively. Finally, density, viscosity and flow characteristics depend on the well control scheme, the reservoir permeability, the cuttings withdrawn from the drilling process with varying lithology. Also, unexpected situations alters fluid flow and rheological properties like, for example, stuck pipe phenomenon; kicks and barite sag, improperly thought to occur under static conditions, but in fact occurring more readily under dynamic, low-shear-rate conditions, resulting in problems such as mud lost circulation.

Traditionally, at normal drilling operations the choke valve is adjusted manually. The fluid composition and pressures are evaluated based on steady state values, and the choke is adjusted accordingly. The main problem of pressure control during drilling is that no measurement of the pressure is available during the periodic disturbance named pipe connection procedure. Wind et al., 2005 employed an electro-magnetic transmission system, which might have problems due to the signal attenuation in deep wells. Reeves et al., 2005 developed a system which integrates, into the drill string, a signal cable, which, however, is disconnected during pipe connection procedure. Jenner et al., 2005 developed a technique named continuous circulating system (CCS), based on a mechanical device able to continuously pumping the drill fluids, even during pipe connections. Nygaard & Naevdal (2006) implemented classic and predictive model control, through simulation studies, concerning underbalanced drilling of a gas-liquid phase system, using the choke opening index, as the manipulated variable, in order to control annulus bottom hole pressure.

A new approach for pressure control while drilling is named Management Pressure Drilling - MPD. MPD creates a pressure profile for staying inside operational window (i.e. pore pressure and fracture pressure), combining hydrostatic pressure control and frictional pressure control, (Fossli & Sangesland, 2006).

Modelling, optimization and control analysis of a drilling process constitutes a powerful tool for operating under desired pressure levels and simultaneously maximizing the penetration rate, which reduces costs. Thus, control and automation of drilling operations is a required activity for future challenge of petroleum engineering, primordially, under a scenario of narrow operational windows. A review analysis unveils that most papers in the literature deals with simulation studies, concerning the process control. In fact, the relevance of the presented paper is building an experimental unit, which presents the drilling process most important characteristics, and also, using the experimental unit to validate classic control strategies. As a result, the main objective of this paper is performing plant identification, through low order transfer function models, and implementing annulus bottom hole pressure control, through manipulating the choke valve index, assuring drilling inside operational envelope, that is, above porous pressure and below fracture pressure.

2. EXPERIMENTAL UNIT

The well drilling unit (Fig. 1) was built using an annulus length of 2.8 m, containing in-line flow – density sensors (Metroval - RHM20), based on Coriolis effect and a pressure transducer (SMAR - LD301-M). The experimental unit manipulated variable candidates, for controlling bottom hole pressure are: a mud pump (Weatherford - 6 HP), connected to a frequency inverter (WEG); a choke valve (ASCO - 290PD-25MM) and butterfly valves (Bray – series30/31), connected to the feed tanks, devices employed for making feasible rate of penetration modification. In fact, the unit has two feeding tanks - water (8 ppg) and mud (15 ppg – pseudo plastic behaviour), making feasible the annulus injection of varying solid concentrations. As a result, this configuration allows the implementation of different rates of penetration, without using a bit, neither solids injection, a very difficult experimental task.

Thus, the oil well drilling system is represented in the structure of the experimental unit, which has an annulus region, pump, choke valve and a pseudo bit producing solids, experimentally implemented through regulating the feeding of water/mud, using the butterfly valves. As a result, the solids injection is directly made by employing the mud tank. It is important to mention that different kinds of drilling phenomena can be captured in the experimental unit. The transient nature of annulus bottom hole pressure, due to the inherent phenomena of well length grow and density/viscosity modification, affecting the hydrostatic pressure and frictional losses, can be implemented using the feeding tanks with water and mud. In fact, feeding the unit with water tank and increasing the relative opening of mud through the butterfly valve, also recycling the unit exit to the water tank, makes the implementation of increasing density levels feasible. This scenario increases both hydrostatic and frictional losses. Besides, feeding the unit with mud and increasing the relative opening of water, through butterfly valve, also recycling the unit exit to the mud tank, makes the implementation of decreasing density levels feasible. This scenario reduces both hydrostatic and frictional losses. The pipe connection procedure can be implemented experimentally through stopping and starting the pump. Also, kicks or lost circulation problems (mud loss) can be implemented experimentally, through increasing or decreasing the pump flow, respectively.

Concerning unit control, different values of rate of penetration can be implemented by varying the relative opening index of the butterfly valves, devices that also can be employed as manipulated variables, in order to control annulus bottom hole pressure. In addition, the choke opening index and the pump flow can be manipulated for closed loop strategies.

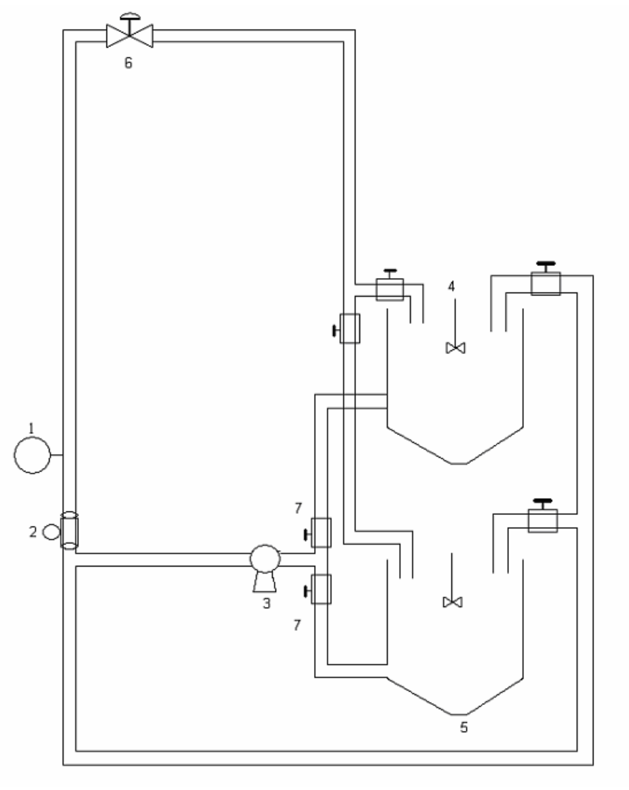

Fig. 1. Experimental unit: 1 – in-line pressure transducer; 2 - in-line flow and density sensors; 3 – helicoidally positive displacement pump; 4 - feed tank (mud density - 8 ppg); 5 – feed tank (mud density – 15 ppg); 6 – choke valve; 7 – butterfly valve.

A dimensional analysis was made in order to assure model and prototype similarity, using Pi Buckingham theorem. However, geometric similarity can only be achieved if the experimental drill string/annulus diameters were made very small due to the typical high well length. However, such experimental configuration would produce experimental problems and was not employed. Besides, experimental tests were carried out using similar prototype fluids (mud densities between 8-15 ppg), for avoiding, for example, the toxic effects of mercury. As a result, in practice, the only feasible dimensional π-group identity between prototype and model concerned Reynolds number.

In addition, a computational program was built in order to monitor and control the drilling unit, using C++ language (Fig.2). A detailed description of the oil well drilling unit may be found in Vega et al. (2011).

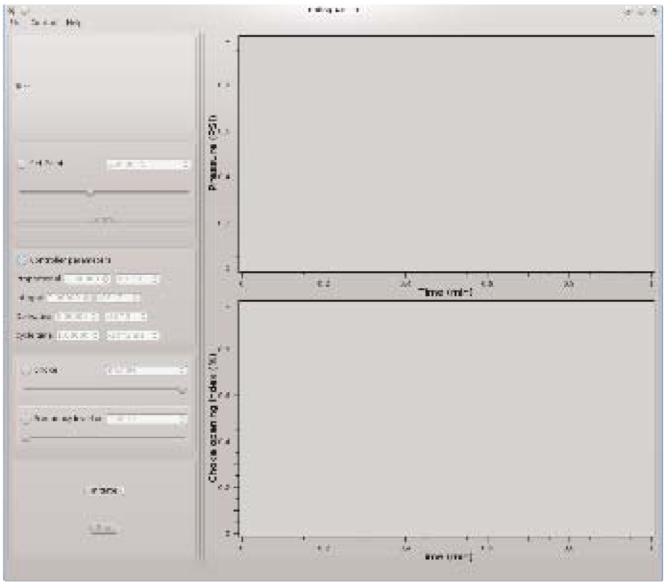

Fig. 2. C++ computational program for plant monitoring and control

3. CONTROL STRATEGY

In this paper, regulating annulus bottom hole pressure, inside operational window, is achieved through manipulation of choke valve opening index. In fact, servo (set point tracking) and regulatory (load disturbance rejections, for example, pipe connection procedure, drilling rate variations, kick and lost circulating problems) control tests can be implemented using the experimental unit.

The hypothesis of linearity is an implicit and necessary prerequisite to most of the classical techniques of process control, which requires superposition principle conformity. In fact, the superposition principle, also known as superposition property, states that, for all linear systems, the net response caused by two or more stimuli is the sum of the responses which would have been caused by each stimulus individually.

The linearity of a system can be measured at both steady and transient states. At steady state, for a constant input (self sustained disturbance), which is the case once the step test has been performed, the output is stationary and the study is reduced to a static comparison between output and input (gain analysis). At transient state, the linearity of the system can be studied through the uniqueness of the transfer function. A linear system must exhibit a constant steady state gain, whatever the shape of the input which is applied (the magnitude of the step disturbance), Seborg et al., 1989.

The identification through low order transfer function approach has proved to be a useful tool and is the most popular framework for empirical model development and classic controller synthesis. The methods of reaction curve (Ziegler-Nichols, 1942) and Sundaresan & Krisnaswany (1977) were employed in order to identify the oil well drilling unit.

Classic feedback control (PI) strategy was experimentally implemented, allowing off-set free responses. The controller tuning method involved subjecting the system to a step change in input, measuring the output as a function of time, and using this response to determine the parameters. In this work, experimental oil well drilling controller tuning employed Ziegler-Nichols, 1942 and Cohen-Coon, 1953 approaches.

4. RESULTS

4.1 Non Linear Analysis

Positive/negative step tests were implemented at oil well drilling experimental unit, for different flow levels (pump frequency inverter at 30, 40, 50 and 60 Hz). In order to implement the experimental test, water (drilling fluid) was pumped through the unit using the choke opening index at 60%. After attaining steady state conditions, positive/negative 35% magnitude steps were implemented at the choke valve index.

As can be observed from Fig. 3, the gains are different for positive and negative step tests, demonstrating the system nonlinear behaviour. Besides, Fig. 3 depicts that gains vary with the magnitude of flow levels and that rich dynamic characteristics are present. The non-linearity of the process can be demonstrated by analyzing the stationary and transient responses. The majority of plant responses correspond to first order models with a dead time, however, delayed second or higher order models can be identified for high fluid flow levels (50Hz and 60 Hz), as the plant presented oscillatory modes. The fact that the transient behaviours are heterogeneous, presenting different transient shapes (Fig.3), attests the non separable non-linearity of the system. However, for control purposes, it would be interesting to determine the domain within which the plant can be considered to be linear.

As a result, it may be necessary to tune a linear controller for each operational level, however, if the linear controller performance presents spurious behaviour, non linear control schemes are the preferred strategy.

Finally, it can be observed that, as the pump flow increases and choke opening index decreases, the difference in shape and magnitude, concerning the positive/negative step responses, is maximized, showing that the system nonlinearity increases. The non linear behaviour observed through the use of the choke device manipulation appears as a system velocity change. As the frictional forces on the fluid and the system restriction (choke index moving to closed position) increase, the experimental unit response becomes faster, situation which also is observed at drilling sites (full scale system). It can be mentioned that another sources of non linear behaviour are due to mud thixotropic properties, process distributed nature and inherent drilling system disturbances.

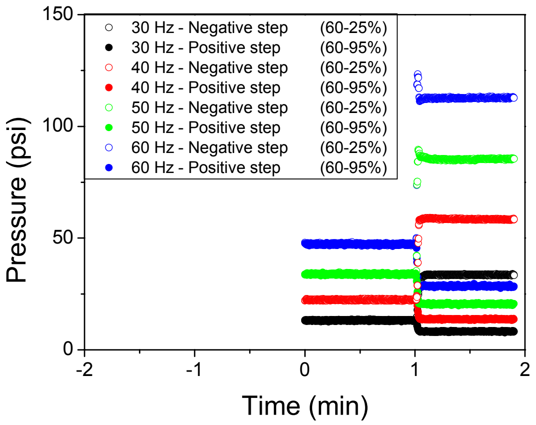

Fig 3. Nonlinear analysis through step test.

4.2 Reaction Curve Method

In order to implement the reaction curve experimentally, water (drilling fluid) was pumped through the unit using the choke opening index at 95%. After attaining steady state conditions, the choke valve index (input variable) varied from 95-25%. The same experimental methodology was performed for the step magnitudes of 95-35% and 95-55%. The reaction curve method corresponds to analysing the annulus bottom hole pressure variation from transient to steady state, in order to identify the process.

For plant identification purposes (Table 1), step disturbances were implemented, varying the opening indexes of the choke valve device from 95-25%, 95-35% and 95-55%, in order to obtain the characteristics parameters of the delayed first order transfer function models: steady state gain (Kp); time constant (τ) and dead time (td). The step tests on choke opening index were performed over the entire plant operational levels: 30 Hz, 40Hz, 50Hz and 60Hz. Table 1 presents the results of plant identification, using the methods of reaction curve (Ziegler-Nichols, 1942) and Sundaresan & Krisnaswany (1977). Sundaresan & Krisnaswany identification procedure, which is based on two point parameter estimation, presented better results when compared with the reaction curve methodology, which employs single point estimation (inflexion point). Table 1 illustrates a slightly increase on plant dead time, which is associated with the delayed response of the valve stem, when increasing perturbation magnitudes are implemented: 40% (choke index: 95-55%), 60% (choke index: 95-35%) and 70% (choke index: 95-25). Concerning time constant, Table 1 indicates that τ decreases, for increasing frequency inverter levels, producing faster plant responses. It can be observed that the steady state gain grows for increasing levels of frequency inverter, at a fixed disturbance value on choke index.

Fig. 4 presents the step response curves for pump frequency inverter at 30, 40, 50 and 60 Hz. Through analyzing Fig.4 - normalized plant output (annulus bottom hole pressure divided by static gain and step magnitude) – it may be concluded that process response is accelerated as the choke opening index is decreased and the pump flow rate increases, in accordance with the plant characteristics parameters of Table 1.

Table 1. Plant identification

Sundaresan & Krishnaswany

frequency	choke index	td	τ	Kp
30 Hz	95-25	0.026802	0.010298	0.336714
	95-35	0.021268	0.010063	0.171333
	95-55	0.017257	0.008154	0.14775
40 Hz	95-25	0.023706	0.006834	0.5986
	95-35	0.020444	0.00737	0.3401
	95-55	0.017108	0.00607	0.260725
50 Hz	95-25	0.022574	0.002707	0.85667
	95-35	0.019624	0.00609	0.553667
	95-55	0.016915	0.005092	0.4115
60 Hz	95-25	0.020348	0.001199	1.118979
	95-35	0.020694	0.001052	0.761268
	95-55	0.017886	0.003457	0.57574

Reaction curve

frequency	choke index	td	τ	Kp
30 Hz	95-25	0.026	0.0112	0.336571
	95-35	0.0216	0.0105	0.171333
	95-55	0.016	0.0088	0.14775
40 Hz	95-25	0.0249	0.0104	0.598714
	95-35	0.0189	0.0148	0.34
	95-55	0.0174	0.0095	0.26075
50 Hz	95-25	0.0198	0.0076	0.857571
	95-35	0.0199	0.0097	0.5535
	95-55	0.0179	0.0062	0.412
60 Hz	95-25	0.0184	0.0054	1.118571
	95-35	0.017	0.0058	0.7599
	95-55	0.0162	0.0065	0.576

4.3 Classic Controller Implementation

Classic PI controller parameters (Table 2) were developed, for different operational levels (30 Hz, 40Hz, 50 Hz and 60 Hz), due to the non linear nature of the drilling plant, through a priori implementation of reaction curve (Ziegler-Nichols, 1942) and Sundaresan & Krisnaswany (1977) identification methodology (Table 1), using the strategies of Ziegler-Nichols, 1942 and Cohen-Coon (Cohen-Coon, 1953). Table 2 illustrates that Cohen-Coon methodology provides less conservative controller tuning parameters (Kc and Ti). In fact, Cohen-Coon methodology provides higher values for Kc and lower values for Ti (Table 2), indicating faster closed loop responses, when compared to Ziegler-Nichols technique. As a result, in order to implement the control tests experimentally, the plant parameters, through Sundaresan & Krisnaswany identification method, were used in the Cohen-Coon tuning technique.

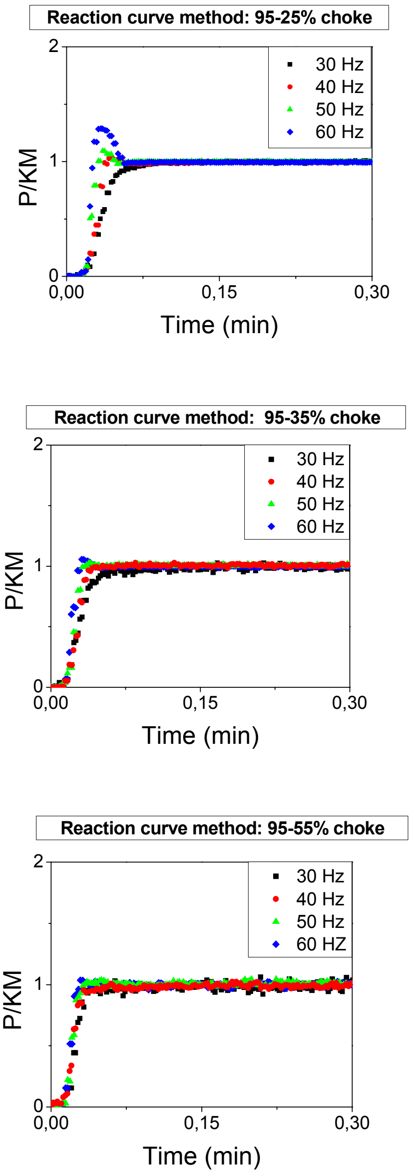

Fig 4. Reaction curve test.

In order to implement experimentally the control tests, water (drilling fluid) was pumped through the unit, using the choke opening index at 95%. After attaining steady state conditions, the choke valve index (manipulated variable) varied, according to the PI controller equation, in order to track annulus bottom hole pressure set points, which were above pore pressure and bellow fracture pressure. The same experimental methodology was performed for each value of the frequency inverter (30 Hz, 40 Hz, 50 Hz and 60 Hz).

Servo control test concerns the implementation of a set point change for annulus bottom hole pressure, which must be tracked through manipulated variable moves (opening index of choke valve device). The opening index is varied according to the controller parameters, fed to the C++ computational program (Fig.2), which remotely operates the plant, using a sampling time of 0.1 seconds.

Table 2. Controller tuning

Sundaresan & Krishnaswany					
		Ziegler-Nichols		Cohen-Coon	
frequency	choke index	Kc	Ti	Kc	Ti
30 Hz	95-25	1.026973397	0.089331733	1.274463144	0.0165975
	95-35	2.485540081	0.070885911	2.971921404	0.015075327
	95-55	2.878244511	0.057515915	3.442260303	0.01222081
40 Hz	95-25	0.433433516	0.079012098	0.572647237	0.012221452
	95-35	0.953976097	0.068139852	1.19900207	0.012150501
	95-55	1.224795528	0.057020964	1.544417096	0.010064524
50 Hz	95-25	0.125975537	0.075237476	0.223251423	0.007065
	95-35	0.504473832	0.065407792	0.654985572	0.010598903
	95-55	0.658387172	0.056378695	0.86089831	0.008961361
60 Hz	95-25	0.047406459	0.067818218	0.121879139	0.004725732
	95-35	0.060094214	0.068973435	0.169560652	0.004577265
	95-55	0.302161776	0.059612372	0.446903037	0.007238957

Reaction curve					
		Ziegler-Nichols		Cohen-Coon	
frequency	choke index	Kc	Ti	Kc	Ti
30 Hz	95-25	1.151887162	0.086658	1.399481956	0.017338918
	95-35	2.553501946	0.0719928	3.039883268	0.015581538
	95-55	3.350253807	0.053328	3.9142696	0.01250501
40 Hz	95-25	0.62785142	0.0829917	0.767038567	0.016275913
	95-35	2.072829132	0.0629937	2.317927171	0.018511796
	95-55	1.884484412	0.0579942	2.204075335	0.013534671
50 Hz	95-25	0.402828889	0.0659934	0.500002524	0.012253488
	95-35	0.79258079	0.0663267	0.943137851	0.014380651
	95-55	0.756630688	0.0596607	0.95889606	0.01036885
60 Hz	95-25	0.236131934	0.0613272	0.310631721	0.009593087
	95-35	0.404077936	0.056661	0.513741488	0.009752677
	95-55	0.626929012	0.0539946	0.771604938	0.010317176

Fig. 5 illustrates the successful servo tests implementation, using water as the drilling fluid, assuring drilling conduction inside operational window, between pore pressure (minimum limit) and fracture pressure (maximum limit), using pump frequency inverter at 30, 40, 50 and 60 Hz. It is important to mention that, although PI controller parameters were available for each operational level (30, 40, 50 and 60 Hz), all experimental operational window control tests (Fig. 5) employed parameters obtained from reaction curve test using 95-35% step magnitude for the choke valve device. As a result, although the drilling plant presented a non linear behaviour, experiments concerning drilling inside operational window did not use adjustable controller parameters.

The same experimental unit control structure can be employed at a real drilling scenario, manipulating the choke opening index, in order to regulate annulus bottom hole pressure. In fact, the manipulation of choke valve is more efficient than inlet mud density, rate of penetration and pump flow variables. The use of inlet mud density alters bottom hole pressure with a significant delay, due to the inherent distributed nature of the system, degrading closed loop performance. Besides, the pipe connection procedure makes unfeasible a control scheme possessing the rate of penetration as the manipulated variable. In fact, at real drilling scenario, the rate of penetration must be maximized and harmonized with the conflicting objective of minimizing specific energy. In addition, unless using a continuous circulating system at the drilling site, pump flow can not be manipulated during the pipe connection procedure. Concerning the PI classic control strategy, a real drilling scenario possesses higher delay than the experimental unit. Delayed pressure transducer monitoring data (100 s) was tested at the experimental unit, results not shown, indicating a performance reduction for the classic PI controller. In fact, the responses presented delays and oscillatory modes, but the operational window envelope constraint was obeyed. Finally, as the feedback control scheme needs measurements of the controlled variable, at a real drilling system, not equipped with wired pipe, that is, not receiving real time pressure data during pumps-off periods, it is suggested that bottom hole pressure be estimated based on a mathematical model, using hydraulic pressure, solid concentration, etc.

5. CONCLUSIONS

An experimental unit was built for regulating recurrent phenomena that occur during the oil well drilling process. The experimental plant contained in-line flow – density sensors, pressure transducer, two feeding tanks, mud pump, choke valve and butterfly valves connected to the feeding tanks. A non linear analysis (step test), plant identification and controller parameter estimation were implemented over different operational levels. An experimental controller was built in order to guarantee inside operational window drilling.

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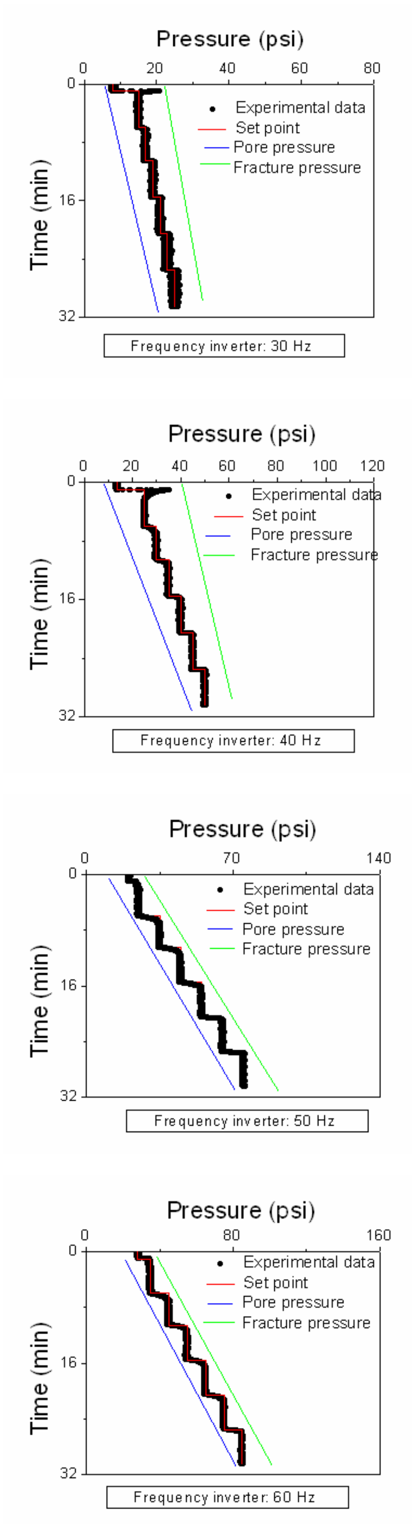

Fig 5. Controlled variable.