Improved IMC for Pressure Control of Oil Wells During Drilling Modeled with an Integrative Term Under Time-Delay

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Abstract. Controlling the pressure of oil wells during drilling can be one of the most complex and dangerous processes of the exploration stage. This study proposes the design of an improved internal model controller (IMC) to control the pressure at the bottom of wells during drilling operations based on Managed Pressure Drilling (MPD). In the first part of this work, there was obtained a mathematical linear model of the process, which is founded on fluid mechanics. The dynamic process showed an integrator element, moreover, is considered the addition of a time-delay between the action of the valve and the response of the downhole pressure variation. In the second part, the improved IMC controller was designed to offset the effect of the integrate term with time delay looking for the best performance and robustness of the system. Finally, the proposed controller is tested by common problems during drilling simulations (loss of fluid, influxes, pipe connection, and loss of pump power) showing its viability.

Keywords: Manage pressure drilling · Wells drilling · Control of oil wells pressure · IMC controller · Two degrees of freedom IMC controller

1 Introduction

One of the most important steps in the exploration of oil deposits is the drilling of wells, in which large sums of money are invested to improve them. During this operation, environmental catastrophes, economic losses, and even fatal accidents can occur, usually due to operational failures. The pressure control during wells drilling generates a high possibility to prevent these inconveniences, making the operation of equipment and the system safer and more accurate. In recent years, new technologies have been developed in this subject. One of the main is the "Managed Pressure Drilling" (MPD) technique that keeps the pressure controlled at the bottom of the well by adding a control pressure in addition to the hydrodynamic pressure (generated by the main fluid circulation pump) and the hydrostatic pressure (due to the depth). This new pressure is given by a throttling valve at the system outlet. Also, during drilling, there are pressure limits that depend

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on the geology of the region to be drilled and it is crucial to maintain the bottom hole pressure between these limits to control the safety of the well's structure [1].

Currently, control theories in drilling systems are being studied considerably due to the benefits that would imply the optimal control of the global system. One of the most attractive feedback control techniques is the PID (Proportional, Integrative, and Derivative), however, the PID needs a good tuning of its parameters [2]. A traditional tuning of the PID parameters can be very effective in cases where the process is linear, invariant in time, and without delay time, which, in practice, does not occur. The addition of a time delay between the acquisition of real data and controller action can be very relevant in controller design to achieve good system performance. The controller design is even more complicated due to instability in processes that have an integrator in the model [3].

This work seeks to compare three types of IMC controllers to control the bottom-hole pressure of oil wells during drilling, also, to determine the type of IMC with the best possible performance characteristics, so this research could be used as a basis for comparison with other future works of more advanced control [2]. The results of the simulation of the three controls are obtained with the methodology IMC, SIMC (Simple IMC), and two degrees of freedom IMC type (proposed), respectively. In industrial control applications, even with reference variations in process operation, good transient response is also desired. In addition, to obtain the desired variable, it is important that the control system eliminates disturbances and/or noise inherent during the drilling process, such as pipe connections, inflows, loss of mud, etc.

2 System Modeling

In this section, the mathematical model of the system that deals with pressure control in oil well drilling is presented. The theoretical foundations used are the Reynolds transport equation to obtain the differential equations that deal with the pressure at the bottom of the well and the flow rate of the control valve. In the well drilling system, the drilling fluid (or mud) travels through the interior of the drill pipes and circulates through the annular zone taking the rocky debris from the drilling to the well surface, passing through the choke valve and back to the mud deposit, closing the system, as illustrated in Fig. 1(a). The resulting equations that describe the system model, and the definition of the variables (Table 1), are shown in Eqs. (1)–(4) [4].

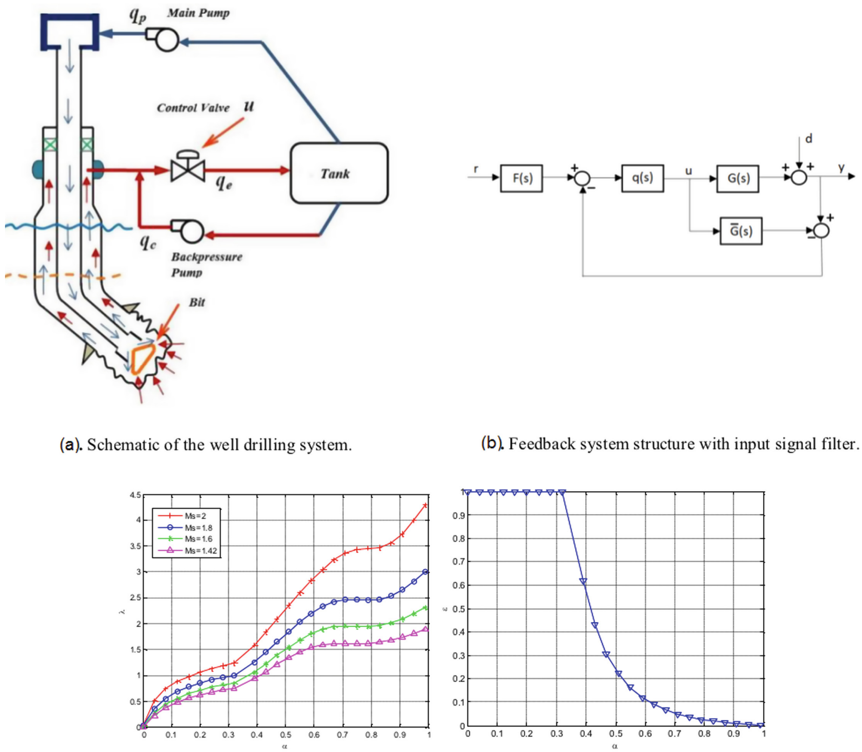
$$V_c\dot{P}_p = \beta_c\big(q_p - q_b\big) \tag{1}$$

$$V_a\dot{P}_e = \beta_a(q_b + q_r + q_c - q_e) \tag{2}$$

$$\dot{q}_b M = P_p - P_e - F_a(q_b + q_r)^2 - F_c q_b^2 + (\rho_c - \rho_a)gh_b \tag{3}$$

$$P_b M = M_c P_e + M_a P_p + M_c F_a(q_b + q_b)^2 - M_a F_c q_b^2 + (M_a\rho_c - M_c\rho_a)gh_b \tag{4}$$

To apply control methodologies, the model must be linearized. For this, the Taylor series is used and the model is linearized around the operating point. First, the input



(a). Schematic of the well drilling system.

(b). Feedback system structure with input signal filter.

(c). Optimal parameters of the two degrees of freedom IMC controller for four robustness levels.

Fig. 1. (a) Schematic of the well drilling system. (b) Feedback system structure with input signal filter. (c) Optimal parameters of the two degrees of freedom IMC controller for four robustness levels.

and output variables of the system are identified. Among the input variables, qp, qr, qc, qe, and hb were considered. The input u is considered to be the sum of the throttling valve flow and the flow produced by the backpressure pump ($u = q_c - q_e$). However, to design the controllers, the process must be modeled according to a predetermined structure. Thus, the transfer function that best approximates the linear model is a first-order equation, with an integrative element, characterized by the parameters: "K" and "τ", as shown in Eq. (5)

$$\frac{P_b(s)}{u(s)} = \frac{K}{s(\tau s + 1)} \tag{5}$$

Table 1. Nomenclature and values of the drilling system parameters.

Parameter	Description	Value	Units
V_a	Ring region volume	96.1327	m^3
V_c	Drill string region volume	28.2743	m^3
P_p	Main pump pressure	–	Bar
P_e	Throttling valve pressure	–	Bar
P_b	Drill pressure	–	Bar
q_e	Throttling valve flow	–	m^3/s
q_b	Drill outlet flow	–	m^3/s
q_p	Main pump flow	0.015	m^3/s
q_r	Reservoir to well flow	0.001	m^3/s
β_a	Annular region compressibility module	7000	Bar
β_c	Column region compressibility module	11000	Bar
q_c	Backpressure pump flow	–	m^3/s
M_a	Ring region mass	1600	$10^{-5}(Kg/m^4)$
M_c	Drill string region mass	5720	$10^{-5}(Kg/m^4)$
M	Sum of Ma and Mc	7320	$10^{-5}(Kg/m^4)$
ρ_a	Density of the ring region	0.0119	$10^{-5}(Kg/m^3)$
ρ_c	Density of the drill string region	0.0125	$10^{-5}(Kg/m^3)$
h_b	Drill Depth	2000	m
G	Gravity	9.81	m/s^2
F_a	Friction force of the annular región	15831	$10^{-5}(m^7/Kg)$
F_c	Friction force of the drill string región	176640	$10^{-5}(m^7/Kg)$

3 Controller Design

The real process of the system and real data of the parameters are used according to Table 1. After replacing the constants in the model (Eq. 5), and since they are different instants between the current state of the choke pressure and the corrective action, the following transfer function is obtained, which considers the effect that occurs due to the delay time. Experimentally and according to the bibliography [5], the time should be approximately 2 s (Eq. 6).

$$\frac{P_b(s)}{u(s)} = \frac{62.22}{s(0.008s + 1)} e^{-2s} \tag{6}$$

To tune and specify the PID parameters according to the proposed methodologies (IMC and SIMC), the transient response performance must first be measured. Thus, in each case, a unit step function was simulated at the initial time as the reference input and, moreover, at the time equal to 100 s., a load disturbance was added. The disturbance was represented by a step function with a value of 0.01, which was used only to quantify, in both methodologies, the rejection of the disturbance, obtaining the value of the Integral Absolute Error of the signal disturbance (IAEd), which consists of the integration of the absolute error of the response signal only related to the disturbance. Next, the quantified performance of the system simulations and respective parameters are presented in the improved methodology [6].

3.1 Improved IMC Controller

[7] Uses the Optimization Method to Determine the PID Parameters that Guarantee the Best Robustness (Ms) and Performance of the System. What Differentiates This Method from the Traditional IMC Method is the Addition of a Filter on the Input Signal in the Feedback, as Shown in Fig. 1(b).

The calculation procedure is formulated as an optimization problem, in which the parameters are obtained by minimizing the performance index of the load disturbance rejection represented by the integrative absolute error, denoted by IAE_d. In addition, a good controller must provide a good level of robustness desired. Thus, in optimization procedures, the robustness measured by the maximum sensitivity function Ms is formulated as a constraint. Finally, although the optimization method employed can be complex, analytical adjustment rules were provided, both for the controller and the setpoint filter (Eq. 7).

$$F(s) = \frac{(\lambda s + 1)(\beta s + 1)}{b^2 s^2 + cs + 1} \tag{7}$$

where $b = \left(2T\beta\lambda + cLT - \beta\lambda^2 + \lambda^2 T\right)/(T + L)$, $c = 2\lambda + \beta + L$, and λ and β are the filter constants that were determined by optimization in [7]. The integrative first-order model with time delay is represented in (8).

$$\overline{G}(s) = \frac{K}{s(\tau s + 1)} e^{-\theta s} \tag{8}$$

Using $\alpha = \theta/(\theta + \tau)$ and $K' = K(\theta + \tau)$ the transformation of $\widehat{S} = (\theta + \tau)s$, the IFOPTD model can be represented as (9).

$$\overline{G}(s) = \frac{K'}{\hat{s}\left[(1 - \alpha)\hat{s} + 1\right]} e^{-\alpha \hat{s}} \tag{9}$$

The method of [7] uses as a model for the projection of the controller with α in the range of 0.01 and 1. The relationship between λ and β is represented with the Eq. (10)

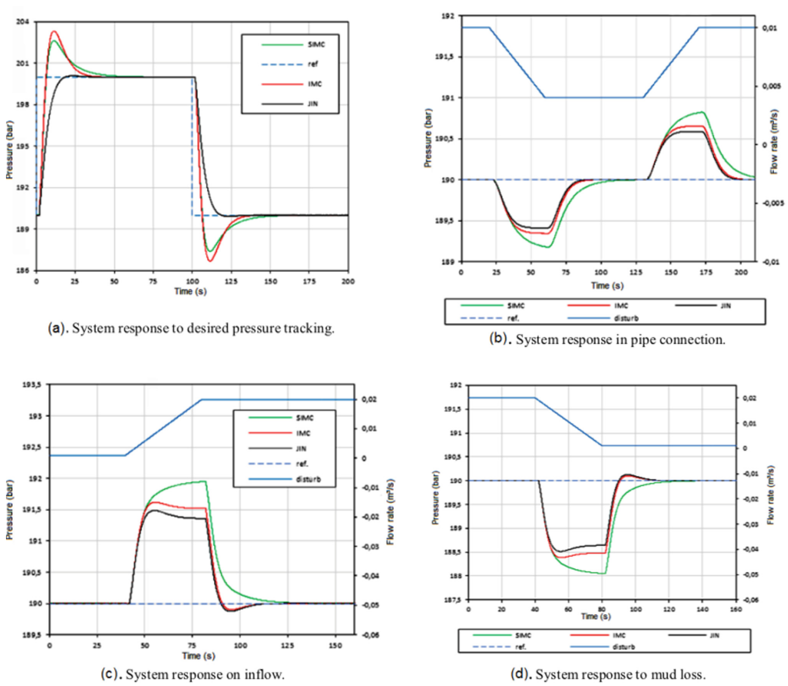
$$\varepsilon = \frac{\beta}{\lambda} = \begin{cases} 1, & 0.01 \le \alpha \le 0.35 \\ \frac{-0.06(\alpha - 1)}{\alpha^3}, & 0.35 < \alpha \le 1 \end{cases} \tag{10}$$

In Fig. 1(c), the PID parameters are illustrated depending on the robustness (Ms) of the system and the parameters.

Finally, the three controllers can be summarized in Table 2 for the analytical determination of the PID parameters for an integrative process with a delay time. The chosen and specified controllers take into account the best performance according to their parameter values. Thus, to equate the conditions between the two methodologies IMC and SIMC [8] the controllers that presented similar robustness were chosen, that is, Ms = 1.8, as shown in Table 2.

Table 2. Quantified performance and PID controller specification for the three IMC control methodology.

	Ms	IAE_d	K_P	K_I	K_D
IMC	1.81	35.1	0.0037	13.008	0.008
SIMC	1.80	39.8	0.004	16.0	0.008
IMC-2Dof	1.80	27,8	0,004	11.4	0,026



(a). System response to desired pressure tracking.

(b). System response in pipe connection.

(c). System response on inflow.

(d). System response to mud loss.

Fig. 2. (a) System response to desired pressure tracking (b) System response in pipe connection. (c) System response on inflow. (d) System response to mud loss.

4 Simulations and Results

During the drilling of wells, disturbances may occasionally occur, causing fluctuations in pressure. In this section, results of the simulations of the studied system and the use of the specified controllers are obtained, however, they were tested and simulated in the real nonlinear process G(s) [9].

Tracking the Desired Pressure. Tracking the Desired Pressure. The first simulations test the specified controllers to assess the system's responses in tracking the signal. Downhole drilling pressure ranges can be very high and vary widely. Thus, in this work, a range of 190–200 Bar was considered. Figure 2(a) shows the performance of the three controllers.

Pipe Connection. During this procedure, when connecting or adding new pipes to the drill string, the 0.015 m^3/s flow mud main pump must be decelerated to zero flow. Thus, only the hydrostatic pressure remains as the only element that influences the behavior of the bottom annular pressure. However, the MPD drilling technique works by connecting the backpressure pump up to approximately 0.004 m^3/s [4]. Figure 2(b) presents the model and the simulation response of the disturbance of the pipe connection upon the flow drop in the main pump. A ramp function from 20 to 60 s was used and in the second 130 it turns on again.

Influx and/or Kick. During drilling operations, it is common to find areas with an influx of gas or oil. When the drill comes into contact with these regions, the fluid, whether gas or oil, flows into the well [1]. An inflow is produced by increasing the reservoir flow variable from 0.001 m^3/s to 0.02 m^3/s in one minute. In Fig. 2(c), for simulation purposes, the inflow can be considered as a positive ramp function of approximately 40 s.

Mud Loss. Mud Loss. Loss of fluid or sludge is defined as the amount of sludge that filters through the porosity of the surface of the permeable formation being drilled. Because of the positive differential pressure between the well pressure and the formation pressure, fluid tends to flow into the formation [6]. For this case, the drop is from 0.02 m^3/s to 0.001 m^3/s. It is observed in Fig. 2(d) the simulated disturbance and the controllers' response.

5 Conclusions

This work deals with the implementation of three types of IMC control methodologies, these methodologies simulated the control of the pressure in oil wells during drilling, the model is presented with an integrator term plus a delay time in the system. The IMC controller with two degrees of freedom proposed by [7] showed better performance in tracking and the presence of disturbances. In the controller with two degrees of freedom, the robustness of the system is inversely proportional to the disturbance, therefore, it presents a better performance in the transient response the better the rejection of disturbances. This phenomenon can be explained considering that the rise time parameter in this controller is directly proportional to the robustness of the system, this tendency is also present in other controllers. Finally, the performance of the IMC controller was considerably improved and tested under conditions similar to the problems that present themselves during drilling. It is believed that this work can be used in comparison with other future works of more advanced control.

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