Hybrid Interval Type-2 Fuzzy PID+I Controller for a Multi-DOF Oilwell Drill-String System

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ABSTRACT The control of multibody drill-string systems is not easy and designing such systems is considered challenging because of the difficulty in the dynamic analysis of its nonlinear characteristics and parametric uncertainties. An optimal hybrid interval Type-2 fuzzy PID+I logic controller (OH-IT2FPID+I) using a practical swarm optimization algorithm for a multi-degree-of-freedom oil well drill-string system is proposed in this paper. The suggested control concept is aimed to overcome several bit sticking troubles and stick–slip vibration by regulating the rotary velocities of drill-string components, especially rotary table velocity and drill bit velocity, to a predefined value. The drill-string system considered here has four degrees of freedom in the down-hole parts and the model takes the nonlinear interactions of the drill bit and the rocks into account, including friction torque and the mud drilling effect. Extensive simulations in Matlab/Simulink and experimental validations through a real-time hardware in the loop (HIL) system were performed to demonstrate the effectiveness of the suggested controller in comparison with sliding mode, Type 1 fuzzy logic and PID controllers. The quantitative comparison performed using simulation results proves that the proposed OH-IT2FPID+I provides higher control performance in terms of settling time and peak overshoot under variation of the weight on bit, the desired drill bit rotary speed, and handling parametric uncertainties. On the other hand, HIL results confirm the control performance provided by the proposed control under all different testing scenarios.

INDEX TERMS Drill-string Vibration, Type-2 Fuzzy PID, Practical Swarm Optimization, Hardware-in-the-Loop, Real-time Simulation.

NOMENCLATURE

| Term            | Definition                          |
|-----------------|-------------------------------------|
| PID             | Proportional–integral–derivative.   |
| FLC             | Fuzzy logic control.                |
| HIL             | Hardware in the loop.               |
| BHA             | Bottom hole assembly.               |
| WOB             | Weight on bit.                      |
| RPM             | Revolution/minute.                  |
| PI              | Proportional-integral.              |
| DOF             | Degrees of freedom.                 |
| SMC             | Sliding-mode controller.            |
| T1FLC           | Type-1 fuzzy logic controller.      |
| IT2FLC          | Interval Type-2 fuzzy logic controller. |
| PSO             | Practical swarm optimization.       |
| H – T1FPID      | Hybrid type-1 fuzzy PID.            |
| H – IT2FPID     | Hybrid interval type-2 fuzzy PID controller. |
| OH – T1FPID + I | Optimal hybrid type-1 fuzzy PID.    |
| OH – IT2FPID + I| Optimal Hybrid interval type-2 fuzzy PID controller. |
| RTS             | Real-time simulation.               |
| ADC             | Analog-to-digital converter.        |
| DAC             | Digital-to-analog converter.        |
| Tm              | Drive torque.                       |
| Tf              | Friction torque.                    |
| \( \Omega_r \)  | Angular position of the rotary ta- |
I. INTRODUCTION

Most applications in the real world involve controllers which need to be tested through simulation and/or experimentally to evaluate and optimize their performance. Simulation is one of the existing solutions used to investigate real-world issues safely.

In the effort to develop the petroleum extraction industry, the control of oil well drill-string systems has become more interesting over the last few years. The main components of oil well drill-string systems are the rotary table, hollow drill pipes, and the bottom hole assembly (BHA) [1]. The BHA is connected to the rotary table by drill pipes and it contains numerous relatively thick drill collars in addition to intermediate stabilizers followed by the drill bit. The whole drill-string is revolved at the surface by the rotary table in order to turn the drill bit [1]. Within the perforation process, several problems may cause it to fail or increase its total cost. The characteristics of a drill-string vary as the drilling operation process progresses, which makes it a complex dynamical system with many indefinite and fluctuating parameters. However, many undesirable vibrations result from the interaction between the drill-string and the borehole. These vibrations are usually the main reason for the failure of the perforation process [1]–[4]. Two particularly harmful phenomena are stick–slip at the bit and a permanently stuck bit. The latter occurs when the bit is unable to rotate, whereas the stick–slip phenomenon occurs when the top rotary table system operates at a constant rotary speed, whereas the bit’s rotary speed varies between zero and up to six times the rotary speed at the surface [1]–[4].

To eliminate these unwanted phenomena, researchers have proposed several passive control methods such as drill-string reconfiguration, bit selection and bit redesign; optimization of BHA configuration; and use of anti-vibration down-hole tools [2]. The functionality of these methods is based on increasing the weight on bit (WOB) and/or decreasing the bit velocity in order to avoid stick–slip vibration. Nevertheless, these methods are not ideal for all situations or always effective [2]–[4]. For example, in [5], the optimal operating conditions that guarantee the stability of drill-string system during drilling are defined as the optimum zone. This zone bounded by the low rate of penetration, stick–slip, and backward and forward whirls in the space of increasing revolution/minute (RPM) and WOB. However, in the case of hard drilling formations, this zone is likely to vanish completely. Consequently, adjusting the drilling parameters to achieve vibration control will usually fail, which limits the performance of passive control methods [2]–[4]. Other researchers have tended to develop active control methods as a result of the enhancements in real-time measurement. In [6], a proportional-integral (PI) regulator was developed and applied. An optimal state feedback control system was designed by Christoforou and Yigit to control the drill-string’s rotational motion in [7]. Serrarens et al. [17] also designed...
a linear $H_{\infty}$ controller in order to suppress stick–slip vibration. In [8], a linear quadratic regulator was developed from a linearized model of a drill-string. Nevertheless, the high nonlinearity of drill-string systems makes the use of linear control methods very limited. In [9], the authors designed the $\mu$-synthesis control method, which considers the modeling errors in the control design process in terms of uncertain WOB. To design this method, the dynamic model of the drill-string system needs to be linearized around an operating point for applying the $\mu$-synthesis theory. For this reason, the effectiveness of the $\mu$-synthesis controller cannot be assured when more degrees of freedom (DOF) are considered. In [10], the authors proposed a nonlinear dynamic inversion control method in order to avoid lateral and the torsional vibrations. Navarro-Lopez and Liceaga-Castro developed a dynamical sliding-mode controller (SMC) to avoid different bit sticking problems in [11]. In [12], Yang Liu presented another SMC that had tolerance for parameter uncertainties and was robust to variations in the WOB. The authors in [13] developed a nonlinear Backstepping controller for drill-string system. Fuzzy-sliding mode was proposed in [18] to enhance the performance of SMC. Furthermore, enhanced control schemes based on fractional-order PID controller were proposed in [14], [15] to improve the control performance provided by the PI regulator. Krama et al. tried to suppress Stick–Slip vibrations by designing a super-twisting controller [16]. However, nonlinear control design is based on a system model in addition to the number of parameters that need to be accurately estimated to effectively design the controller. Thus, a comprehensive comparison has been conducted among several control strategies for stick-slip suppression in oil-well drill-string system, the outcome of this comparison is summarized in Table 1.

| Control strategy                                      | Year | Control accuracy | Design Complexity | Implementation complexity |
|-------------------------------------------------------|------|-----------------|-------------------|--------------------------|
| Optimum Zone [5]                                       | 2010 | Low             | Medium            | Moderate                 |
| PID controller [6]                                     | 2003 | Medium          | Low               | Easy                     |
| Optimal state feedback control [7]                    | 2003 | Medium          | Medium            | Easy                     |
| linear $H_{\infty}$ controller [8]                    | 1998 | Medium          | Medium            | Easy                     |
| linear quadratic regulator [8]                        | 2000 | Medium          | Medium            | Easy                     |
| $\mu$-synthesis control method [9]                    | 2010 | Medium          | Medium            | Easy                     |
| nonlinear dynamic inversion control method [10]       | 2003 | Medium          | Medium            | Easy                     |
| sliding-mode controller (SMC) [11]                    | 2007 | High            | High              | Easy                     |
| Modified sliding-mode controller (SMC) [12]           | 2014 | High            | High              | Easy                     |
| Backstepping controller [13]                          | 2005 | High            | High              | Easy                     |
| FO-PID controller [14]                                | 2019 | Medium          | Low               | Easy                     |
| Enhanced FO-PID controller [15]                       | 2021 | Medium          | Low               | Easy                     |
| Super-Twisting Controller [16]                        | 2021 | High            | High              | Easy                     |

Because of the fast development of signal processor capacities and the evolution of industrial informatics, fuzzy logic control (FLC) has found many applications in industrial control [19]–[22]. The major advantage of FLC theory is the potential to set up controllers without relying on a mathematical model of the system under consideration. For this reason, FLC theory is suitable for designing robust controllers of unknown or uncertain systems. Within the literature, Type-1 FLC (T1FLC) has been widely used in several applications [23]–[28]. However, the effectiveness of T1FLC is limited because of its reliance on expert knowledge to select the optimal parameters of the controller. To alleviate this problem, interval Type-2 FLC (IT2FLC) has recently been investigated instead of T1FLC because it offers more DOF to deal with nonlinearities and uncertainties [29]–[33]. Despite the advantages offered by IT2FLC, other researchers have tended to combine conventional PID control with the T1FLC or IT2FLC in order to achieve better control performance [34]–[37].

To obtain better performance control for multi-DOF oil well drill-string systems, IT2FLC is combined with conventional (proportional–integral–derivative) PID to design a hybrid fuzzy PID control structure. The optimal parameters of the suggested controller are selected by using a practical swarm optimization (PSO) algorithm. The optimal hybrid interval type-2 fuzzy PID+I logic controller (OH-IT2FPID+I) proposed in this paper is aimed to overcome several bit sticking troubles and stick–slip vibration by regulating the rotary velocities of the drill-string components, especially rotary table velocity and drill bit velocity, to a desired value. To evaluate the proposed structure, numerical simulations in Matlab/Simulink and experimental validations through real-time hardware in the loop (HIL) will be performed.
Moreover, the performance of the suggested controller will be compared with sliding mode controllers, T1FLC, and conventional PID under variation of the WOB, the desired drill bit rotary speed, and parametric uncertainties.

The main contributions of this paper, in summary, are as follows:

- Design of a new optimal hybrid interval Type-2 fuzzy PID+I logic controller (OH-IT2FPID+I) for oil-well drill-strings.
- The OH-IT2FPID+I coefficients are optimally selected via a particle swarm optimization (PSO) algorithm.
- In comparison with several control strategies, such as PID, Sliding mode control (SMC) proposed in [11], Modified SMC proposed in [12] and optimal hybrid Type-1 fuzzy PID+I logic controller (OH-T1FPID+I), the proposed OH-IT2FPID+I offers the best control performance.
- The OH-IT2FPID+I was implemented in real time in the laboratory. The performance of the OH-IT2FPID+I was confirmed on a hardware in the loop (HIL) test based on an OPAL-RT 5600 real-time simulator and a dSPACE 1103 card.

This paper is structured as follows: after the Introduction, the discontinuous torsional model for the drill-string, including the bit–rock interaction, is presented in Section 2. Section 3 describes the proposed control structures. This section is divided into three parts. The first part discusses the suggested structures based on T1FLC, the second part presents the suggested structures based on IT2FLC, then the PSO algorithm used for tuning the coefficients of the controllers is presented in the third part. The simulation and HIL results are shown and discussed in Sections 4 and 5, respectively. Finally, the conclusions are drawn in Section 6.

II. DYNAMIC MODELING OF DRILL STRING SYSTEM

Dynamic modeling of drill-strings is the basis of analyzing, monitoring, and suppressing harmful vibrations. Over the last 50 years, extensive work has been carried out to explain the physical phenomenon in real boreholes mathematically. The lumped-parameter model is the most popular for drill-string dynamics and torsional vibration analyses.

The drill-string is considered as a mass–spring–damper system. It can be easily modeled via an ordinary differential equation. This representation of the finite-dimensional structure offers an overall depiction of the dynamics, at different levels of the string, from one to many DOF. A mechanical representation of the drill-string system based on four DOF is shown in 1. It consists of four damped inertias represented by four disks. The inertias are mechanically linked to each other through shafts by the dampers \(d_t, d_{t1}, d_{p2}\), and the torsional springs \(k_t, k_{tl}, k_{tb}\) [38]. A sequence of disks corresponding to the rotary table on the top (r), the drill pipe (p), the drill collars (l), and the drill bit (b) represent the lumped-parameter model. The rotary table has a large damped inertia to prevent rapid changes in angular velocity and is driven by an electric motor with torque \(T_m\) through a gearbox. Through a series of interconnected drill pipes, the length of the drill-string can be up to many kilometers [39]. The drill pipes are made from metallic tubes. The bottom part is made up of a weightier pipe called the BHA. The drill bit is surrounded by drilling mud, which dissipates the energy of the drill bit and the strong torque imposed on the bit [40]. The drill bit is also subjected to a frictional torque \(T_{fb}\) that represents the bit–rock interaction. The drilling system’s geometric and material properties are summarized in 1. The rotary table is assumed to be fixed, but the bit is free [41].

Based on the aforementioned characteristics of a drill-
string, a set of state equations that represent the dynamic behavior of the drill-string system are detailed in Eq. (1), whereas the state vector of the drill-string system is defined in Eq. (2) [42].

\[ \begin{align*}
\dot{\Omega}_r &= \frac{d_r}{j_r} (\dot{\Omega}_t - \dot{\Omega}_p) - \frac{k_t}{j_r} (\Omega_r - \Omega_p) \\
\dot{\Omega}_p &= \frac{d_p}{j_p} (\dot{\Omega}_t - \dot{\Omega}_p) + \frac{k_t}{j_p} (\Omega_r - \Omega_p) \\
\dot{\Omega}_t &= \frac{d_t}{j_t} (\dot{\Omega}_p - \dot{\Omega}_t) + \frac{k_t}{j_t} (\Omega_p - \Omega_t) \\
\dot{\Omega}_b &= \frac{d_b}{j_b} (\dot{\Omega}_t - \dot{\Omega}_b) + \frac{k_b}{j_b} (\Omega_l - \Omega_b) \\
\end{align*} \]  

(1)

\[ \mathbf{X} = [\dot{\Omega}_r, (\Omega_r - \Omega_p), \dot{\Omega}_p, (\Omega_p - \Omega_t), \dot{\Omega}_t, (\Omega_l - \Omega_b), \dot{\Omega}_b]^T \]  

(2)

Where: \( j_r, j_p, j_t, j_b \) are the inertia coefficients of the rotary table, drill pipes, drill collars, and drill bit, \( \Omega_r, \Omega_p, \Omega_t, \Omega_b \) are the angular position of the rotary table, drill pipes, drill collars, and drill bit, \( \Omega_r, \Omega_p, \Omega_t, \Omega_b \) are the angular velocity of the rotary table, drill pipes, drill collars, and drill bit, \( k_t, k_l, k_{lb} \) are the torsional stiffness, \( d_r, d_t, d_{lb} \) are torsional damping, \( d_t \) is the viscous damping coefficient, \( T_m \) is the drive torque, \( T_{ob}(X) \) is the torque on the bit, \( X \) is the system state vector, \( T_{fb}(X) \) is the torque required for crushing and cutting the rock and the friction along the BHA.

For the sake of simplicity, Eq. (2) is defined as follows:

\[ \mathbf{X} = [x_1, x_2, x_3, x_4, x_5, x_6, x_7]^T \]  

(3)

Finally, the state equations of the drill-string system are given in Eq. (4), using the simplified representation of Eq. (3) to facilitate the analysis.

\[ \begin{align*}
x_1 &= \frac{1}{j_r} [-(d_r + d_t)x_1 - k_t x_2 + d_l x_3 + T_m] \\
x_2 &= x_3 - x_7 \\
x_3 &= \frac{1}{j_p} [d_p x_1 + k_t x_2 - (d_t + d_t)x_3 - k_t x_4 + d_l x_5] \\
x_4 &= x_3 - x_5 \\
x_5 &= \frac{1}{j_t} [d_t x_3 + k_t x_4 - (d_t + d_b)x_5 - k_{lb} x_6 + d_{lb} x_7] \\
x_6 &= x_5 - x_7 \\
x_7 &= \frac{1}{j_b} [d_{lb} x_5 + k_{lb} x_6 - (d_{lb} + d_b)x_7 - T_{ob}(x)] \\
\end{align*} \]  

(4)

Torque on the bit is given by the following equation:

\[ T_{ob} = T_v (x_7) + T_{fb}(X) \]  

(5)

Where \( T_v(x_7) \) is given by Eq. (6):

\[ T_v(x_7) = d_b x_7 \]  

(6)

Where \( T_v(x_7) \) influence of the drilling mud on the bit’s behavior.

Most of the energy provided by the motor at the top surface is dissipated at the drill bit through bit–rock interaction [4]. The contact between the bit and the rock is the primary source of vibrations in a drill-string. Therefore, it is essential for an analysis of the vibration mechanism to establish a bit–rock interaction model [43]. Throughout the literature, many friction models are available [12], [13], [44], [45]. The most frequently used models over recent years are the Stribeck model [12], [12], [13], [44] and Karnopp’s model [12], [44], [45]. The problems with the Stribeck model are the instability issue and discontinuity at zero speed. The static characteristics of friction cannot be accurately defined. In order to solve the abovementioned problems, bit–rock interaction has been modeled by Karnopp’s model [45], as shown in 3. It considers both frictional and cutting contact. The reaction torque is computed via the mathematical model given by Eq. (7).

\[ T_{fb}(x) = \begin{cases} 
T_{eb}(x) & \text{if } |x_7| < D_v, \ |T_{eb}| \leq T_{sb} \\
T_{sb} \text{sign}(T_{eb}(x)) & \text{if } |x_7| < D_v, \ |T_{eb}| > T_{sb} \\
T_{eb}(x_7) & \text{if } |x_7| \geq D_v 
\end{cases} \]  

(7)

\[ T_{eb} = d_{lb} (x_5 - x_7) + k_{lb} x_6 - d_b x_7 \]  

(8)

\[ T_{sb} = w_{ob} R_b u_{sb} \]  

(9)

\[ u_{b}(x_7) = u_{eb} + (u_{sb} - u_{eb}) e^{-\frac{x_7}{T_{eb}}} \]  

(10)

\[ T_{eb} = w_{ob} R_b u_{b}(x_7) \]  

(11)

Where \( T_{sb} \) is the static friction torque, \( T_{eb} \) is the Coulomb friction torque, \( T_{eb}(X) \) is the breakaway torque, \( R_b \) is the bit radius, \( u_{b}(x_7) \) is the dry friction coefficient of the bit, \( u_{sb}, u_{eb} \) is the static and Coulomb friction coefficients, and \( WOB \) is the weight on Bit.

The lumped-parameter model of the drill-string can be written in a multivariable form as follows [46]:

\[ x(t) = M_1 X(t) + M_2 T_m + M_3 T_{fb}(X) \]  

(12)

where \( M_1, M_2, \) and \( M_3 \) are matrices, which are derived from Eq. (4).
III. THE PROPOSED CONTROL SCHEME

In general, the PID controllers are not suitable for nonlinear multi-DOF drill-string systems with one control input and multiple variables to be controlled. To overcome these problems and obtain better system performance, an optimal hybrid fuzzy PID+I controller was designed for the drill-string system under consideration by using two types of fuzzy logic control. The complete structure of the closed-loop control scheme is depicted in 3. In this control scheme, the control torque \( u \) has two parts, the first one \( u_1 \) for driving the angular velocities of rotary table and drill bit to a preferred value while avoiding the bit sticking oscillations and reducing the influence of parametric uncertainties, and the second one \( u_2 \) for enhancing the tracking error between the angular velocities. Therefore, the output of the suggested controller is given as:

\[
 u = u_1 + u_2
\]  
(13)

Where \( u_1 \) is the output of the hybrid fuzzy PID controller that will be detailed in the next subsections and \( u_2 \) is the output of the adding integrator, given as:

\[
 u_2 = k_i^+ \int [x_1 - x_7] dt
\]  
(14)

Where \( k_i^+ \) is the integral coefficient of the adding integrator.

A. HYBRID TYPE-1 FUZZY PID CONTROLLER

Fuzzy control theory is selected because it offers a robust controller, whereas no modeling is essential for multi-DOF drill-string systems. Fuzzy logic is an empirical control strategy, which is able to exploit expert knowledge by means of mathematical operations [47]. Generally, T1FLC is implemented by four successive calculation stages: the fuzzifier, the rules, the inference engine, and the defuzzifier [32]. The fuzzifier transforms the numerical signals into a normalized fuzzy subset. Next, the fuzzy values are assessed by the inference engine, which comprises a set of if–then rules. In the last stage, the inference engine’s output is applied to the defuzzifier in order to transform it into a control objective [32]. The developed hybrid type-1 fuzzy PID controller H-T1FPID is schematized in 4. In this scheme, the error tracking and its derivative for the angular velocities of the rotary table are considered as the controller inputs:

\[
e = k_e(\Omega^* - x_1)
\]  
(15)

\[
 C_e = k_{ce}\frac{d(\Omega^* - x_1)}{dt}
\]  
(16)

where \( k_{ce} \) and \( k_{ce} \) are normalizing coefficients for the controller inputs, and \( \Omega^* \) represents the desired angular velocity of the rotary table. The fuzzifier inputs have been implemented via five symmetric triangular membership functions. While, seven singleton fuzzy sets have been chosen for the defuzzifier output in order to reduce the computational effort. Both the input and output values are converted into an equal fuzzy range \([-1, 1]\) to simplify the design complexity. The Min–Max algorithm is applied as the inference engine, which includes 25 if–then rules. All the membership functions and rules for the H-T1FPID are illustrated in 4. The center of gravity algorithm is used for the defuzzifier stage and the output of the H-T1FPID is computed as:

\[
u_2 = k_pU + k_i\int U dt + k_d\frac{de}{dt}
\]  
(17)

Where \( k_p \) is the denormalizing proportional coefficient, \( k_i \) is the denormalizing integral coefficient, \( k_d \) is the denormalizing derivative coefficient, and \( U \) is the fuzzy output. The aim of the conventional derivative term in the suggested H-T1FPID is to enhance the stability of the controlled drill-string and decrease the settling time.

B. HYBRID TYPE-2 FUZZY PID CONTROLLER

Compared with the T1FLC system, Type-2 fuzzy logic control has proved its capability to minimize the effect of uncertainties in many industrial applications [28]–[32]. As can be seen in 5, the IT2FLC structure has five main stages: the fuzzifier, the rules, the inference engine, the type reducer, and the defuzzifier. In the first stage, the physical inputs are converted into linguistic variables using interval Type-2 fuzzy sets instead of Type-1 fuzzy sets. The inference engine in IT2FLC uses the same rules as a T1FLC to generate the output of Type-2 fuzzy sets. Next, the type reducer transforms the outputs of the Type-2 fuzzy sets to Type-1 fuzzy sets. Lastly, the defuzzifier processes the fuzzy control action to obtain a crisp output [28]. 6 presents the suggested hybrid interval type-2 fuzzy PID controller (H-IT2FPID), which is an extension of the T1-FLC-PID controller. Its output is computed in the same way in Eq.(17). It can be observed that the IT2-FLC-PID inputs are the same as those used by H-T1FPID. The input signals are fuzzified via five triangular interval Type-2 fuzzy sets. In addition, as fuzzifier output, seven Type-2 singleton fuzzy sets are used. Therefore, the H-IT2FPID requires 25 fuzzy control rules; these rules are exactly the same as those of the H-T1FPID. All the rules for H-IT2FPID are shown in 6. To activate the fuzzy rules, the Max–Min method is used as the inference engine. The defuzzifier is the last stage in implementing the IT2FLC, where the center-weighted average algorithm is used to transform the reduced fuzzy sets of the output into crisp value. Many types of reduction algorithm have been applied for IT2FCL. In this work, an appropriate reducer algorithm, Karnik–Mendel [28], is chosen.

C. PARTICLE SWARM OPTIMIZATION

Nowadays, several researchers tend to employ the bio-inspired optimization algorithms to determine the optimal coefficients of control schemes [48]–[52]. The bio-inspired optimization algorithms are flexible and get their optimal solution by tuning of the control scheme gains in the search optimization problems. In this paper, a PSO algorithm that was inspired by the flocking behavior of birds was used in
FIGURE 3. Suggested control scheme for the drill-string system

FIGURE 4. Suggested structure of the H-T1F1PID controller

FIGURE 5. Structure of the IT2FLC system
order to determine the optimal coefficients of the proposed controller [48], [49]. Consequently, an appropriate objective function $J$, which has to be minimized, was formulated as:

$$J = \int_0^\infty \lambda_1 t |\Omega - x_1| dt + \int_0^\infty \lambda_2 t |x_1 - x_7| dt$$
$$+ \int_0^\infty \lambda_3 t |u_1| dt + \int_0^\infty \lambda_4 t |u_2| dt \quad (18)$$

Where $\lambda_1, \lambda_2, \lambda_3$ and $\lambda_4$ are the weighting factors. These weighting factors are selected by trial and error to provide a good trade-off between minimizing the errors while ensuring that the control signal was not too big. However, the issue of optimally tuning the controller coefficients can be expressed as a typical constrained optimization problem with six coefficients $(k_e, k_{Ce}, k_p, k_i, k_d, k_i^+)$: Minimize $J(x)$ with $x=(k_e, k_{Ce}, k_p, k_i, k_d, k_i^+)$, subject to:

$$k_{e}^{\text{min}} \leq k_e \leq k_{e}^{\text{max}}$$
$$k_{Ce}^{\text{min}} \leq k_{Ce} \leq k_{Ce}^{\text{max}}$$
$$k_p^{\text{min}} \leq k_p \leq k_p^{\text{max}}$$
$$k_i^{\text{min}} \leq k_i \leq k_i^{\text{max}}$$
$$k_d^{\text{min}} \leq k_d \leq k_d^{\text{max}}$$
$$k_i^{+\text{min}} \leq k_i^+ \leq k_i^{+\text{max}}$$

Initially, the PSO algorithm needs to start by creating particles inside the search space randomly. After executing the simulation model of oil-well drill string system, the particles fly around the search space with their assigned velocities during each iteration with the hope of finding the optimal coefficients for the proposed controller. Then, the fitness of each particle is calculated using Eq.18. From the stored results, the velocity of each particle is updated depending on the particle’s current velocity, the particle’s individual best solution, and the current global optimum solution. Furthermore, the particle’s position is updated repeatedly depending on the new velocities until the stopping requirements are met.

The flowchart of the PSO algorithm used for assessing the performance of the objective function and tuning the optimal controller coefficients is represented in 7 [48], [49].

IV. SIMULATION RESULTS

In this section, simulations are conducted for a four DOF drill-string system in MAT-LAB/Simulink, where the mathematical model considers the nonlinear interaction of the drill bit and the rocks, including friction torque and the mud drilling effect. The parameters of the overall system are presented in Table 2. The performance of the proposed OH-T1FPID+I and OH-IT2FPID+I are compared with conventional methods under the following scenarios: a step change in reference angular velocity, variation in the WOB when the reference angular velocity is constant, and parametric uncertainties under constant reference angular velocity. The optimized coefficients of the controllers and the parameters of the PSO algorithm are also listed in Tables 3 and 4.

The results obtained by applying the proposed OH-IT2FPID+I controller are presented in 8. At time 35 s, the proposed control scheme was applied to eliminate the stick–slip vibration. It is seen clearly that the angular velocities of both the rotary table and the drill bit are quickly stabilized to the reference angular velocity with small peak overshoots at $t = 56.25$ s and $t = 63.12$ s, respectively.

As shown in 9, a step increase in reference angular velocity from 12 rad/s to 16 rad/s was applied at 150 s. A large step decrease in reference angular velocity from 16 rad/s to 8 rad/s occurred at 300 s. Despite these critical changes, the proposed OH-IT2FPID+I controller guaranteed a fast
TABLE 2. Numerical values for the drill string system parameters [11]

| system Parameters | Value  | Units   |
|-------------------|--------|---------|
| $J_r$             | 930    | kg.m$^2$|
| $J_l$             | 750    | kg.m$^2$|
| $J_p$             | 2782.25| kg.m$^2$|
| $J_b$             | 471.9698| kg.m$^2$|
| $k_t$             | 698.06 | N.m/rad |
| $k_{tt}$          | 1080   | N.m/rad |
| $k_{tb}$          | 907.48 | N.m/rad |
| $d_t$             | 139.6126| N.m.s/rad|
| $d_{tt}$          | 190    | N.m.s/rad|
| $d_{tb}$          | 181.49 | N.m.s/rad|
| $d_b$             | 50     | N.m.s/rad|
| $WOB$             | 100    | kN      |
| $R_b$             | 0.155575| m       |
| $T_m$             | 10     | kN.m    |
| $D_v$             | 10$^{-6}$| rad/sec|
| $d_v$             | 425    | N.m.s/rad|
| $\mu_{sb}$        | 0.8    | --      |
| $\mu_{cb}$        | 0.5    | --      |
| $\gamma_b$        | 0.9    | --      |

FIGURE 7. Flowchart of the PSO algorithm

FIGURE 8. Simulated responses with the OH-IT2FPID+I controller with a constant reference angular velocity (12 rad/s); (a) Angular velocities of the rotary table and the drill bit; and (b) control torque

FIGURE 9. Simulated responses of the OH-IT2FPID+I controller during variation in reference angular velocity; (a) Angular velocities of the rotary table and the drill bit; and (b) control torque
TABLE 3. The optimal coefficients of the controllers

| Controller         | $k_e$   | $k_{Ce}$ | $k_p$  | $k_i$  | $k_d$  | $k_i^+$ |
|--------------------|---------|----------|--------|--------|--------|---------|
| OH-T1FPID+I        | 0.0149  | 0.0805   | 9.821  | 1100   | 99.999 | 6.732   |
| OH-IT2FPID+I       | 0.0915  | 0.4722   | 15.05  | 5574.1 | 0.1100 | 5.254   |

TABLE 4. PSO algorithm parameters

- Number of particles in a swarm: 10
- Maximum number of iterations: 150
- Acceleration coefficients: 2
- Minimum inertia coefficient: 0.6
- Maximum inertia coefficient: 0.9
- The upper and the lower bounds of $k_e$: [0.01, 10]
- The upper and the lower bounds of $k_{Ce}$: [0.01, 10]
- The upper and the lower bounds of $k_p$: [0.1, 100]
- The upper and the lower bounds of $k_i$: [10, 10000]
- The upper and the lower bounds of $k_d$: [0.1, 100]
- The upper and the lower bounds of $k_i^+$: [0.1, 100]

response time with a small overshoot/undershoot.

10 depicts the simulation results of the proposed OH-IT2FPID+I controller during variation in WOB under a constant reference angular velocity. The latter is set to 12 rad/s while the WOB changes suddenly from 100 kN to 80 kN at 150 s, and from 80 kN to 100 kN at 300 s. The OH-IT2FPID+I controller provided high performance control (small overshoot/undershoot and a short settling time) under these sudden changes in WOB.

The simulated responses of the OH-IT2FPID+I controller under parametric uncertainties is illustrated in 11. In this case, the reference angular velocity is set to 12 rad/s but the parameters $J_r$, $k_t$, $d_t$, and $d_r$ are changed. It should be noted that the parametric uncertainties do not degrade the performance of the proposed OH-IT2FPID+I controller, which achieved a fast response time and a small overshoot.

To demonstrate the advantages of using the suggested control scheme, the OH-IT2FPID+I controller is compared with OH-T1FPID+I, the SMC proposed in [11], the SMC proposed in [12], and conventional PID controllers. The simulated responses with different controllers during variation in reference angular velocity are presented in 12. It can be observed in this figure that the SMC algorithms proposed in [11] and [12] present a large undershoot during greater decreases in reference angular velocity, which can lead to system instability. The simulated responses with different
controllers under variation in WOB are illustrated in 13. In 14, the proposed OH-IT2FPID+I controller shows high performance control in terms of settling time and peak overshoot of the different controllers under the different scenarios as detailed in Table 5. We can confirm that the proposed OH-IT2FPID+I provided better control performance than other conventional techniques including the OH-T1FPID+I, the SMC proposed in [11], the SMC proposed in [12], and conventional PID controllers under all the scenarios tested.

V. EXPERIMENTAL RESULTS BASED HIL METHODOLOGY

To confirm the high performance of the proposed OH-IT2FPID+I presented in simulation section, a laboratory test setup of a drill-string system that used the HIL testing strategy was built around dSPACE 1104 and OPAL-RT 5600 components, as shown in 15. The dSPACE takes the role of a real-time controller, in which drill-string is controlled in real time. On the other hand, the OPAL-RT serves as a power plant simulator, which simulates the drill-string in real-time. The major advantage of the real-time simulator is that it can simulate the drill-string model, including its behavior as fast as would be carried out in the real world. It was developed for high-speed real-time simulation (RTS), in which the simulation of a real system can be achieved with high accuracy. The proposed drill-string controller is implemented together in dSPACE. The dSPACE receives the required signals (drill bit and rotary table velocity) from the OPAL-RT through analog-to-digital converter (DAC) channels to calculate the reference drive torque via the proposed OH-IT2FPID+I controller and send it to the dSPACE via DAC channels. The OPAL-RT is configured with MATLAB, which communicates with RT-LAB software to generate real-time code. The real-time code is generated by MATLAB in...
combination with dSPACE real-time blocks and downloaded in dSPACE hardware to be executed in real time. The real-time data can be displayed and recorded via the real-time interface of the RT-LAB software. Moreover, the data can be displayed on an oscilloscope through the available DAC channels that are available on the connector panel of the OPAL-RT. Note that the parameters used in HIL testing are similar to those used in the simulation. The HIL setup is shown in 16.

First, the performance of the proposed OH-IT2FPID+I controller is tested under a step increase in reference angular velocity from 12 rad/s to 16 rad/s and large step decrease in reference angular velocity from 16 rad/s to 8 rad/s as shown in 17. The proposed OH-IT2FPID+I controller assured a fast response time with a small overshoot/undershoot during these critical changes. However, it is worth mentioning that the transient period in both cases was longer than that obtained in the simulation. This difference is justified by the DAC delay within the hardware, which made the results closer to real-world results. Then, another HIL tests were conducted to investigate the robustness of the system against variation in the WOB while the reference angular velocity is set to 12 rad/s (18). The scenario started with WOB equal to 100 kN. Once the drill-string was loaded with a WOB of 50 kN, the reference torque was reduced and the angular velocity of the drill-string experienced some oscillation before it stabilized at the reference. The WOB was increased in real-time to 100 kN again to test the controller under a sudden increase in WOB. The proposed controller performed well, rejecting the WOB variations and maintaining the angular velocity of the drill-string at its reference. To test the robustness of the proposed controller in the case of parametric uncertainty, four parameters are changed in real time as shown in 19. The HIL results prove the effectiveness of the proposed OH-IT2FPID+I in parameters uncertainties rejection while the angular velocities keep tracking their reference perfectly.
TABLE 5. Quantitative performance analysis of different controllers in terms of settling time and overshoot/undershoot.

| Scenario 1: Step variation in the reference angular velocity |
|------------------------------------------------------------|
| Angular velocity of the rotary table | Angular velocity of the drill bit |
|----------------|-----------------|-------------------|-------------------|
| Step increase in the angular velocity reference 12 rad/s | Step increase in the angular velocity reference 16 → 8 rad/s |
| PID | 92.52 | 3.79 | 92.68 | 2.91 | 44.52 | 0.55 | 44.55 | 0.61 | 53.11 | 1.38 |
| SMC[12] | 39.45 | 2.25 | 47.56 | 6.73 | 24.67 | 1.18 | 32.72 | 1.20 | 32.72 | 1.20 | 32.72 | 1.20 | 45.52 | 3.67 | 56.78 | 8.00 |
| SMC[13] | 46.56 | 3.83 | 46.56 | 1.89 | 24.69 | 1.20 | 32.72 | 2.52 | 45.52 | 3.67 | 56.78 | 8.00 |
| OH-T1FPID+I | 30.70 | 0.81 | 30.70 | 0.81 | 35.32 | 1.60 | 10.54 | 0.28 | 22.04 | 0.48 | 20.37 | 0.61 | 21.33 | 0.48 | 20.37 | 0.61 |
| OH-IT2FPID+I | 27.92 | 0.97 | 27.92 | 0.97 | 34.43 | 3.35 | 11.72 | 0.56 | 23.13 | 0.28 | 20.35 | 0.61 |

| Scenario 2: Step variation in the WOB |
|--------------------------------------|
| Angular velocity of the rotary table | Angular velocity of the drill bit |
|----------------|-----------------|-------------------|-------------------|
| Step decrease in the WOB 80 kN | Step decrease in the WOB 100 → 80 kN |
| PID | 50.82 | 1.88 | 51.92 | 2.38 | 50.54 | 1.85 | 51.25 | 2.35 |
| SMC[12] | 19.25 | 0.92 | 26.64 | 2.32 | 19.32 | 0.90 | 26.86 | 2.23 |
| SMC[13] | 19.25 | 0.92 | 26.64 | 2.32 | 19.32 | 0.90 | 26.86 | 2.23 |
| OH-T1FPID+I | 13.41 | 0.77 | 13.41 | 0.77 | 13.95 | 0.78 | 13.96 | 0.78 |
| OH-IT2FPID+I | 12.98 | 0.77 | 12.98 | 0.77 | 13.95 | 0.78 | 13.96 | 0.78 |

| Scenario 3: Step variation in the reference angular velocity in the case of parametric uncertainty |
|----------------------------------------------------------------------------------------------------------------|
| Angular velocity of the rotary table | Angular velocity of the drill bit |
|----------------|-----------------|-------------------|-------------------|
| Step increase in the angular velocity reference 0 → 12 rad/s |
| PID | 95.15 | 3.44 | 94.96 | 3.86 | 95.15 | 3.44 | 94.96 | 3.86 |
| SMC[12] | 39.05 | 1.60 | 47.57 | 4.94 | 49.04 | 1.60 | 48.62 | 4.94 |
| SMC[13] | 39.05 | 1.60 | 47.57 | 4.94 | 49.04 | 1.60 | 48.62 | 4.94 |
| OH-T1FPID+I | 28.74 | 1.21 | 31.22 | 1.08 | 30.64 | 1.21 | 31.22 | 1.08 |
| OH-IT2FPID+I | 28.74 | 1.21 | 31.22 | 1.08 | 30.64 | 1.21 | 31.22 | 1.08 |
VI. CONCLUSION
In this paper, an IT2FLC was combined with conventional PID to design a robust fuzzy PID control structure for a multi-DOF drill-string system. The practical swarm optimization (PSO) algorithm was used to select the optimal coefficients for the suggested controller. The goal of this controller was to overcome several bit sticking problems and stick–slip vibration by regulating the rotary velocities of the drill-string components, especially the rotary table’s velocity and the drill bit’s velocity to a predefined value. The drill-string system model used in this study had four-DOF down-hole parts and the model accounted for the nonlinear interaction of the drill bit and the rocks, including friction torque and the mud drilling effect. To demonstrate the effectiveness of the suggested controller compared with conventional methods, a series of simulations in Matlab/Simulink and experimental validations with a real-time hardware in the loop (HIL) system were performed. Both simulation and HIL results show that the proposed OH-IT2FPID+I can achieve effective control performance under extreme operating condition including variation of the WOB, the desired drill bit rotary speed, and parametric uncertainties. Where, it has been confirmed from the quantitative comparison with OH-T1FPID+I, two advanced SMC, and PID controllers that the response time of the proposed control scheme is shorter than that of other controllers, while the overshoot/undershoot of the proposed OH-IT2FPID+I is lower than that of other controllers in the most of the conducted case studies.

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