Stick-Slip Vibration Mitigation in Rotary Drilling Systems Using a Particle Swarm Optimization-based PID Controller under Varying Weight on Bit Conditions

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Abstract: Rotary systems on drilling rigs are susceptible to various types of vibrations, which can lead to equipment damage, reduced borehole quality, decreased drilling efficiency, and increased non-productive time. These vibrations are typically managed through manual adjustments of drilling parameters, often resulting in higher costs and reduced productivity. To address this challenge, automatic control strategies have been developed, though the robustness of these controllers is still under refinement. Recently, a promising approach has emerged by combining PID controllers with Particle Swarm Optimization (PSO) algorithms, demonstrating significant success in other applications. However, its effectiveness in mitigating stick-slip vibrations, particularly under varying Weight on Bit (WOB) conditions, in rotary systems on drilling rigs has not been fully tested. This paper examines the application of a PSO-optimized PID controller to enhance the robustness of vibration mitigation strategies in rotary drilling systems, taking into account the effect of WOB. The results demonstrate that the proposed controller outperforms previously developed control approaches, offering superior vibration suppression even under varying WOB conditions.

Keywords: Proportional–integral–derivative controller (PID); particle swarm optimization (PSO); rotary system on a drilling rig; stick-slip vibrations; controller robustness

1 Introduction

A rotary drilling system is a critical tool in the petroleum industry used to extract oil and gas from underground reservoirs. It consists of two main components: the surface equipment and the subsurface drill string. The surface equipment includes the hoisting system, rotary table, pumps, and drilling fluid (mud) conditioning system. The drill string comprises the Bottom-Hole Assembly (BHA), which consists of thick-walled tubular (drill collars) and specialized downhole instruments. Stabilizers stabilize drill collars, and the compressive force applied to the drill bit during operation is referred to as the Weight on Bit (WOB). Similarly, the mechanical torque transmitted from the rotary table to the drill string is known as the Torque on Bit (TOB). Drilling mud plays a crucial role in lubricating and cleaning the system, making it an indispensable component of rotary drilling operations [1, 2].

During drilling, various unwanted vibrations may occur, including axial, lateral, and torsional vibrations, often simultaneously. Among these, stick-slip vibrations are the most damaging, as they can trigger or amplify other vibration modes. This study focuses on minimizing stick-slip vibrations, which are considered the primary cause of such issues [3, 4].

In recent years, mitigating torsional vibrations has been a significant area of research. For instance, Tang et al. [5] demonstrated that reducing WOB could eliminate stick-slip vibrations. Another study by Tang et al. [6] highlighted the impact of increasing rotary table speed on reducing torsional vibrations, though it did not account for drill string stiffness. Sliding mode control techniques have also been explored [7, 8] to prevent oscillations and release the drill bit when stuck. However, these approaches often suffer from high stabilization times due to the chattering phenomenon associated with the sliding input surface [9, 10].

Empirical studies, such as Liu's work [11], and advanced control strategies, including back-stepping control explored by Abdulgalil and Siguerdidjane [12], have shown promising results in mitigating stick-slip vibrations. Hybrid controllers have also been investigated; for example, Mendil et al. [9] combined PID control with sliding mode techniques, while their later studies proposed sliding mode controllers specifically for minimizing torsional vibrations.

Although previous approaches have shown satisfactory results, further advancements are necessary to enhance the robustness and efficiency of vibration suppression in rotary drilling systems. The main contributions of this work include the development of a PID controller whose parameters are optimally tuned using the Particle Swarm Optimization (PSO) algorithm, ensuring improved convergence, enhanced stability, and effective suppression of stick-slip vibrations. This optimized controller is specifically applied to mitigate torsional oscillations under dynamically changing WOB, accounting for the nonlinear and time-varying nature of real-world drilling conditions. Furthermore, a detailed robustness analysis is conducted to evaluate the controller's performance under varying WOB scenarios, addressing practical reliability concerns. The proposed approach is validated through a scenario-based simulation framework that assesses controller behavior across diverse operating conditions, including constant, step-up, and step-down reference signals, thereby closely reflecting real field applications.

The primary control objectives are to minimize oscillations in the drill bit's angular velocity, suppress stick-slip vibrations, and ensure rapid convergence to steady-state operation under varying WOB conditions. To meet these goals, an optimization problem is formulated in which the PSO algorithm determines the optimal PID gain parameters by minimizing the Integral of Time-weighted Absolute Error (ITAE). This strategy aims to improve vibration suppression and enhance system stability [13, 14].

The rest of the manuscript is organized as follows: Section 2 provides an overview of vibrations associated with the drilling system. Section 3 presents the mathematical model of the drill string. Section 4 details the controller design, including the formulation of the optimization problem and the PSO algorithm used for PID tuning. Section 5 presents the simulation results, analyzing both open-loop and closed-loop system behavior, and includes a comparative evaluation of the controller under different scenarios. Finally, the conclusion summarizes the key findings and outlines directions for future research.

2 Modes of Vibrations

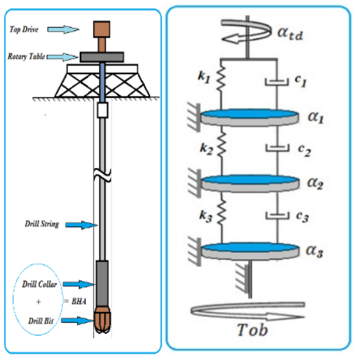
The drilling process can be affected by undesirable vibrations, including axial, lateral, and torsional vibrations, which can lead to various issues, such as bit bounce, whirling, and stick-slip [15]. Torsional vibration, in the form of stick-slip, is considered the most harmful type of vibration, as it can cause other types of vibration [15]. Axial vibration, also known as bit-bounce, occurs when the drill bit loses contact with the formation [4, 5]. The transverse side-to-side motion of the drill string characterizes whirling. Lateral vibrations can cause significant damage to the BHA, although they are difficult to detect at the surface [16, 17]. Stick-slip occurs when the string does not rotate smoothly due to insufficient rotary torque, resulting in elastic deformation and energy storage [18]. Severe stick-slip can cause costly downtime, leading to downhole motor failures, twist-off, or drill bit damage. Stick-slip can occur due to either rock-bit interaction or interaction between the drill string and borehole wall, as demonstrated in [1].

3 Mathematical Model for Stick-Slip Vibrations

This section presents a mathematical model based on a mass-spring-damper system consisting of three elements.

3.1 Drilling String Model

The used mass-spring-damper model has three degrees of freedom, where the upper disc symbolizes the rotary table, the middle disc represents the tool string, and the lower disc corresponds to the drill bit [3]. The details of the model's parameters are succinctly outlined in Table 1. Furthermore, Figure 1(a) illustrates the schematic diagram of the rotary drilling system, while Figure 1(b) depicts its three degrees of freedom model. The latter is mathematically described by equation (1) [9].



(a) (b)

Figure 1

Rotary drilling systems: (a) Schematic diagram, (b) Equivalent mass-spring-damper three-element model [9]

$$\begin{cases} \ddot{\alpha}_1 = \frac{1}{J_1}\left(c_1(\dot{\alpha}_{td} - \dot{\alpha}_1) - k_1(\alpha_{td} - \alpha_1) - c_2(\dot{\alpha}_1 - \dot{\alpha}_2) - k_2(\alpha_1 - \alpha_2) - \mu\dot{\alpha}_1\right) \\ \ddot{\alpha}_2 = \frac{1}{J_2}\left(c_2(\dot{\alpha}_1 - \dot{\alpha}_2) + k_2(\alpha_1 - \alpha_2) - c_3(\dot{\alpha}_1 - \dot{\alpha}_2) - k_3(\alpha_2 - \alpha_3) - \mu\dot{\alpha}_2\right) \\ \ddot{\alpha}_3 = \frac{1}{J_3}\left(c_3(\dot{\alpha}_2 - \dot{\alpha}_3) + k_3(\alpha_2 - \alpha_3) - \mu\dot{\alpha}_2 - Tob\right) \end{cases} \quad (1)$$

Table 1

Parameters description for the designed rotary drilling model [9, 15]

Parameter	Description	Unit
α_{td}	The top drive angular displacement	[rad]
$\alpha_{i=1,2,3}$	The angular displacements of the rope section i	[rad]
$k_{i=1,2,3}$	Torsional stiffness coefficient of the rope section i	[N.m/rad]
$c_{i=1,2,3}$	Internal damping coefficient of the rope section i	[N.m.s/rad]
μ	Wall friction coefficient	[N.m]

$j_{i=1,2,3}$	The inertia of the rope section i	[kg.m[2]]
Tob	The torque on bit	[N.m]

The values of the system parameters are:

$k_1 = k_2 = k_3 = 481.29\ N.m/rad$

$j_1 = j_2 = 999.35\ Kg.m^2$, $j_3 = 127.27\ Kg.m^2$

$c_1 = c_2 = 51.38\ N.m.s/rad$, $c_3 = 39.79\ N.m.s/rad$

$\mu = 10\ N.m.$

For the transition to the state space representation, we implement the following variable changes:

$u = \dot{\alpha}_{\mathrm{td}}$ (the input signal is defined as the angular velocity of the top drive)

$x_1 = \dot{\alpha}_1$

$x_2 = \dot{\alpha}_2$

$x_3 = \dot{\alpha}_3$

$x_3 = \alpha_{\mathrm{td}} - \alpha_1$

$x_5 = \alpha_1 - \alpha_2$

$x_6 = \alpha_2 - \alpha_3$

then the equation (1) is written as given by equation (2).

$$\begin{cases} \dot{x}_1 = \frac{c_2 + c_{td} + \mu}{J_1} x_1 - \frac{c_2}{J_1} x_2 + \frac{k_1}{J_1} x_4 - \frac{k_2}{J_1} x_5 + \frac{c_1}{J_1} u \\ \dot{x}_2 = \frac{c_2}{J_2} x_1 - \frac{c_2 + c_3 + \mu}{J_2} x_2 + \frac{c_2}{J_2} x_3 + \frac{k_2}{J_2} x_5 - \frac{k_3}{J_2} x_6 \\ \dot{x}_3 = \frac{c_3}{J_3} x_2 - \frac{c_2 + \mu}{J_3} x_3 + \frac{k_3}{J_3} x_6 - \frac{1}{J_3} Tob \\ \dot{x}_4 = \dot{\alpha}_{td} - \dot{\alpha}_1 = u - x_1 \\ \dot{x}_5 = \dot{\alpha}_1 - \dot{\alpha}_2 = x_1 - x_2 \\ \dot{x}_6 = \dot{\alpha}_2 - \dot{\alpha}_3 = x_2 - x_3 \end{cases} \tag{2}$$

3.2 Rock-Bit Interaction Term

Various mathematical functions have been employed in previous studies to represent the interaction between the rock and the drill bit [9,15]. In this research work, we use the generalized model proposed in [1] for the particular system under consideration.

$$Tob = \mu_n N_r \left(\frac{x_3}{\sqrt{x_3^2+\Omega_0^2}} + \frac{p\Omega_0 x_3}{x_3^2+\Omega_0^2} \right) + Dx_3 \left(\frac{x_3}{\Omega_1} - 1 \right) \tag{3}$$

Where Tob represents the torque on the bit, the model coefficients are summarized in Table 2.

Table 2

Parameters used in the rock-bit general term [9, 15]

Parameter	Description	Value
μ_n	Friction coefficient	40 [nm]
N	The force vector	9.81 * Wob
r	The contact radius vector	0.1 [m]
Ω_0	Chain transition speed	1
Ω_1	Transition speed for the well	31.4159
p	The initial friction parameter	1.5
D	The linear damping vector	0.28

4 Controller Design

4.1 PID Controller

Due to its ease of use in tuning and reliable performance, the PID controller is used; the PID control equation is commonly represented as follows:

$$C(t) = K_P e(t) + K_i \int_0^t e(t) d\tau + K_d \frac{de(t)}{dt} \tag{4}$$

Where: $C(t)$, $e(t)$ are the controller output and the error signal respectively, K_P $K_i$and, K_d are the PID proportional, integral and derivative gains respectively. One of the main factors in defining the PID controller performance is the tuning of its parameters, in order to achieve this in optimal way; we proposed the use of particle swarm optimization.

4.2 Optimisation Problem Formulation

The controller design is formulated as an optimization problem with an objective function, design variables, and constraints [21, 22]. It is characterized by a continuous function, where both the input and output arguments are real-valued variables. The design variables represent the PID controller gains $K = [K_P, K_i, K_d]$

which must be optimized to minimize the error between the desired and actual system responses, as expressed in equation (5). The optimization is achieved by minimizing the objective function, which is defined as the Integral of Time-weighted Absolute Error (ITAE), given in equation (6).

$$e(t) = y_{ref}(t) - y_{sys}(t) \quad (5)$$

$$J_{ITAE} = \int_0^T t|e(t)|\mathrm{d}t \quad (6)$$

Where: $e(t)$ is the error signal, $y_{ref}(t)$ is the reference signal and $y_{sys}(t)$ is the system output under PID control with gains K.

this optimization is subject to constraints on the PID parameters, given by:

$$K_{min} < K < K_{max} \quad (7)$$

Where K_{min}, K_{max} is the lower Bound and Higher Bound of the gain K

The resulting formulation guides the search for optimal PID gains that not only minimize tracking error but also inherently promote system stability, as the ITAE criterion penalizes oscillatory or divergent behavior.

4.3 Particle Swarm Optimization

Particle swarm optimization is a bio-inspired evolutionary algorithm, originally developed by *Kennedy and Eberhart* in 1995 [20], that utilizes the behavior of social groups, such as bird flocks or fish schools, to optimize a given problem. In PSO, a population of particles, each representing a potential solution in the search space, is initialized with random positions and velocities. The particles move in the search space, adjusting their flight based on their individual experiences and interactions with other particles in the swarm. The goal is to effectively explore the solution space by swarming particles towards the best-fit solution discovered in previous iterations, aiming to discover improved solutions and ultimately converge on a single optimal solution. PSO has been applied in various fields due to its ability to solve optimization problems efficiently and converge on optimal solutions [19].

Mathematically, the i^{th} particle's state is represented by $x_i = (x_{i1}, x_{i2}, \dots, x_{id})$, and its best previous solution by $p_i = (p_{i1}, p_{i2}, \dots, p_{id})$. The particle's velocity, or position change rate, is denoted by $v_i = (v_{i1}, v_{i2}, \dots, v_{id})$. Furthermore, the best solution obtained thus far by the entire swarm, known as g_{best}, is represented as

$p_g = (p_{g1}, p_{g2}, \dots, p_{gd})$. During each iteration of the PSO process, each particle adjusts its position and velocity by moving towards both its personal best *(p)* and the best solution found by the entire swarm *(g_{best})*. The fitness function is used to evaluate the performance of particles and determine whether the optimal solution has been reached. The particle's movement is governed by mathematical equations typically expressed as:

$$V_{id}(t+1) = v_{id}(t) + c_1 r_1 \left(p_{id}(t) - x_{id}(t)\right) + c_2 r_2 \left(p_{gd}(t) - x_{id}(t)\right) \tag{8}$$

$$x_{id}(t+1) = x_{id}(t) + v_{id}(t) \tag{9}$$

Where: $p_{id}(t)$, $p_{gd}(t)$ represent the personal best and global best solutions at time t, $x_{id}(t)$, $v_{id}(t)$ represent position and the velocity of the particles at time *t*, $v_{id}(t+1)$ and $x_{id}(t+1)$ represents the update velocity and position of the particle at time $t+1$, c_1 and c_2 are the cognitive and social learning coefficients, respectively, and r_1, and r_2 are random numbers between 0 and 1, w is the inertia factor.

4.4 Implementation of PSO-Based PID Tuning

In this study, the PSO is employed in an offline framework to optimize the PID parameters, using the system model described in Equation (2). The PSO algorithm begins by initializing a swarm of particles, where each particle represents a candidate solution within the defined search space. The PID gain values associated with each particle are randomly generated within specified bounds, denoted as K_{min}, K_{max}.

Given the three-dimensional nature of the optimization problem corresponding to the three PID gains $K = [K_p, K_i, K_d]$, the positions and velocities of the particles are maintained in matrices of size 3×Swarm Size. A swarm size of 50 particles is selected to ensure adequate exploration of the solution space and to increase the likelihood of converging to the global optimum.

To evaluate the quality of each candidate solution, the PID parameters represented by each particle are applied to a closed-loop simulation of the system [23, 24]. The simulation output is used to compute the control error over time, from which the performance index ITAE previously defined is calculated. This ITAE value serves as the fitness value for the particle, reflecting how well the corresponding PID gains regulate the system. Based on these fitness evaluations, particles update their personal best positions, and the global best is identified [25].

We investigate numerically the implementation of the PID-PSO algorithm in the rotary system on a drilling rig. The proposed approach is illustrated in Figure 2.

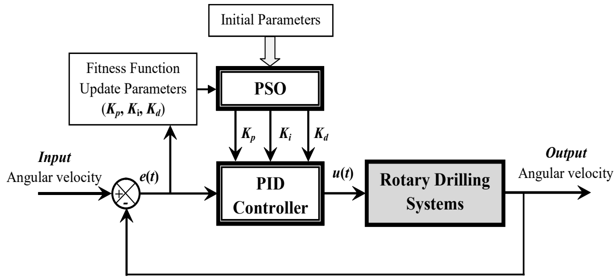


Figure 2
Diagram of the proposed PID-PSO controller for the rotary drilling system

The PSO algorithm operates using a two-level loop structure. The inner loop iterates over each particle to simulate the system, evaluate its fitness, and update its velocity and position according to the PSO equations. The outer loop governs the number of iterations, often referred to as "bird steps," which controls the convergence dynamics of the swarm across successive iterations. The flowchart in Figure 3 illustrates a detailed representation of the proposed PSO-based PID tuning procedure.

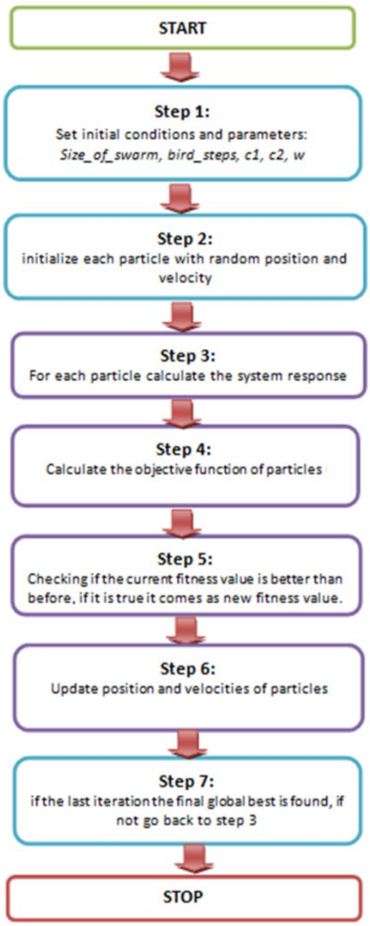


Figure 3
Flowchart illustrating the tuning procedure of the proposed PSO-based PID

5 Results and Discussion

This section presents a comprehensive analysis of the simulation results to assess the effectiveness of the proposed PSO-based PID controller in suppressing stick-slip vibrations in rotary drilling systems. The analysis begins with an evaluation of the open-loop system dynamics, highlighting the inherent instability and poor tracking performance in the absence of control (Section 5.1). This is followed by the implementation of a conventional PID controller, manually tuned using MATLAB tools, to establish a baseline for performance comparison (Section 5.2). While this approach offers some improvement, it remains insufficient in eliminating oscillations or achieving a satisfactory settling time. To address these limitations, a PSO-optimized PID controller is then applied (Section 5.3), resulting in significantly enhanced transient response and reduced stick-slip effects. Further validation is conducted through two practical simulation scenarios: the first considers constant reference input with varying weight on bit (WOB) values (Section 5.3.1), while the second evaluates the system's ability to track step changes in reference speed, simulating real drilling operation demands (Section 5.3.2). Finally, a comparative analysis is presented (Section 5.4), consolidating performance metrics across the open-loop system, conventional PID, and PSO-optimized PID configurations, to highlight the superiority of the proposed control strategy under diverse operational conditions.

5.1 Open-loop Responses

Figure 4 illustrates the step response of the rotary drilling system operating in open-loop. The simulation was conducted with a reference angular velocity of 20 rad/s applied over the time interval 0 < t < 500 s, and the weight on bit (WOB) was set to 170 Nm.The plot reveals that the drill bit angular velocity exhibits significant oscillations, resulting in a long settling time. Moreover, the system's dynamic and static characteristics are not satisfactory, and its ability to track the rotary table speed is poor. These observations suggest that the uncontrolled system's performance is suboptimal, and a suitable controller must be designed to improve the system's response.

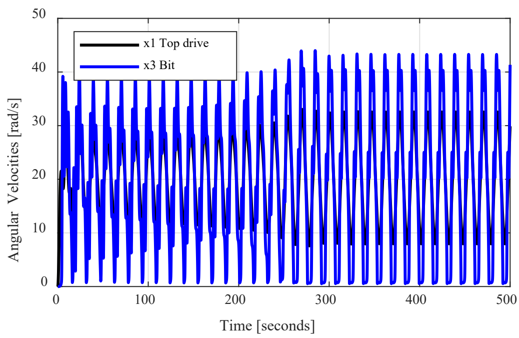


Figure 4

Open-loop Angular velocity responses of the top drive and the drill bit

5.2 Closed Loop PID Control Responses without PSO

In this subsection, the PID controller parameters were obtained without the use of Particle Swarm Optimization (PSO). Initially, manual tuning was attempted using MATLAB's PID Tuner, following system linearization. The Extended Symmetrical Optimum Method (ESOM), as proposed by Precup (1996) [27], was also applied to calculate the controller parameters. However, due to the high-order dynamics and nonlinear friction effects in the system, the ESOM tuning resulted in unstable responses. To ensure practical stability and performance, the final PID parameters were selected using MATLAB's robust auto-tuning feature, yielding values of Kp = 0.01, Ki = 0.0025, and Kd = 0.01. A reference speed of 20 rad/s was applied for 500 seconds with the WOB fixed at 170 Nm during the simulation. The corresponding closed-loop system response is shown in Figure 5.

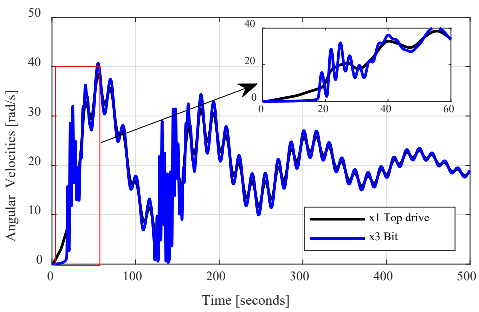


Figure 5
The closed-loop responses of rotary system on a drilling rig with PID controller without PSO

As demonstrated in Figure 5, the designed PID controller did not sufficiently suppress the stick slip, as the oscillation remains considerable and can be very harmful. Therefore, it is highly necessary to consider more advanced PID tuning parameters in order to improve controller efficiency. Henceforth, PSO has been employed to overcome this issue, as discussed in the next subsection.

5.3 Closed Loop PID Control Responses with PSO

In this subsection, the PSO algorithm was initialized with the parameters given in Table 3 and the optimization process resulted in the determination of the following PID controller parameters: K_p = 1.1722, K_i = 0.3253, and K_d = 8.5164. The simulation results of the drilling model, controlled by the PID controller tuned by PSO, are presented in Figure 6. The system was simulated with a constant reference angular velocity of 20 rad/s over a duration of 500 seconds, while maintaining the weight on bit (WOB) at 170 Nm.

Table 3
Particle swarm optimization algorithm parameters

Parameter	Description	Value
n	Size of the swarm N° of birds	50
bird_setp	Maximum number of birds steps	50
dim	Dimension of the problem	3
Kmax	Upper limits of (Kp, Ki, Kd)	[10 10 10]
Kmin	Lower limits of (Kp, Ki, Kd)	[0 0 0]

c1	PSO constant c1	0.12
c2	PSO constant c2	1.2
w	PSO momentum or inertia	0.9

Figure 6 illustrates the step response of a drilling rotary system equipped with a PID controller tuned using the PSO algorithm to mitigate stick-slip vibrations in the drilling system. As shown in the figure, the vibrations have been effectively eliminated in a shorter time than conventional PID controllers. Moreover, the response time of the system has been significantly reduced in comparison to the system without the controller, indicating that the designed controller has a faster regulation time. Furthermore, no overshoot is observed after 30 seconds, indicating the system's stability. To investigate this observation further, we conducted a series of scenarios to mimic current cases in petroleum drilling fields, as detailed in the next subsections.

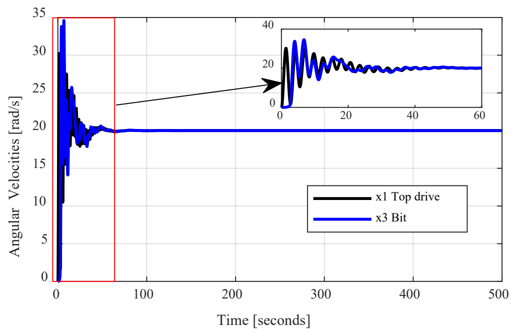


Figure 6

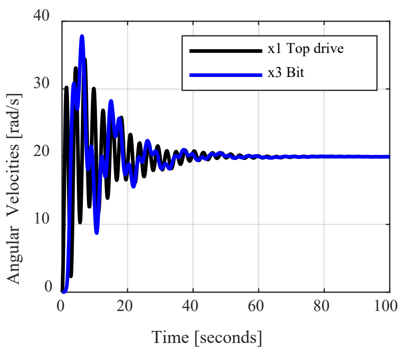
The angular velocity responses of top drive and drill bit in closed-loop configuration of rotary drilling systems with PID controller tuned by PSO

5.3.1 Scenario 1: Constant Input Reference

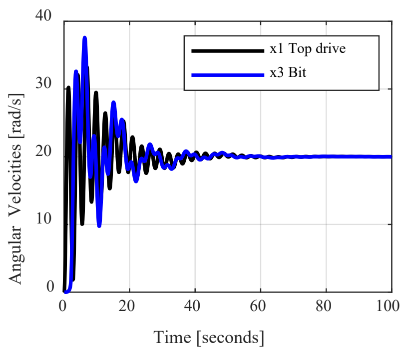
The evaluation of the controller's performance under constant input reference and varying Wob conditions can provide insights into the controller's ability to regulate the drilling system in different operating conditions. The evaluation was conducted in five different scenarios, as summarized in Table 4. Figure 7 depicts the obtained outcomes. The results revealed that the PSO-based PID controller with the optimal parameters in Table 4 was able to suppress the stick-slip vibrations and track the reference in scenarios 1.1 to scenario 1.3; this was not the case in scenarios 1.4, 1.5 and 1.6, which can be attributed to the fact that the optimal parameters were determined using PSO when the Wob is equal to 100 N.m. Moreover, the results obtained in scenarios 1.1, 1.2, and 1.3 demonstrate the effectiveness of PSO in enhancing the performance of the PID controller in suppressing stick-slip vibrations. Furthermore, these findings underscore the importance of selecting an optimal Wob value to maximize drilling efficiency during the drilling process. To further assess the performance of the proposed controller, additional real-field scenarios were executed, as outlined in the next subsections.

Table 4
Parameters for each scenario in this closed loop configuration

Scenarios	Wob [N.m]	Kp	Ki	Kd	Input Type [Rad/s]
1.1(a)	10	1.1722	0.3253	8.5164	20
1.2(b)	50	1.1722	0.3253	8.5164	20
1.3(c)	100	1.1722	0.3253	8.5164	20
1.4(d)	200	1.1722	0.3253	8.5164	20
1.5(e)	500	1.1722	0.3253	8.5164	20
1.6(f)	1000	1.1722	0.3253	8.5164	20



(a)



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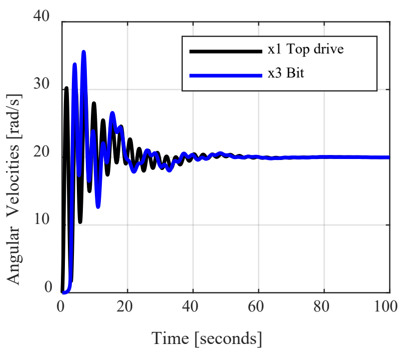

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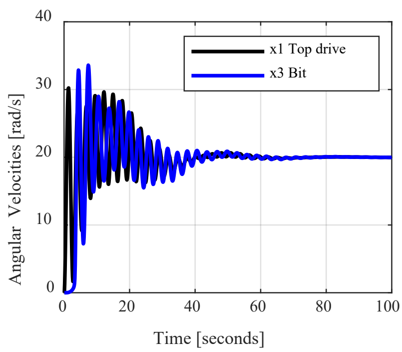


(d)

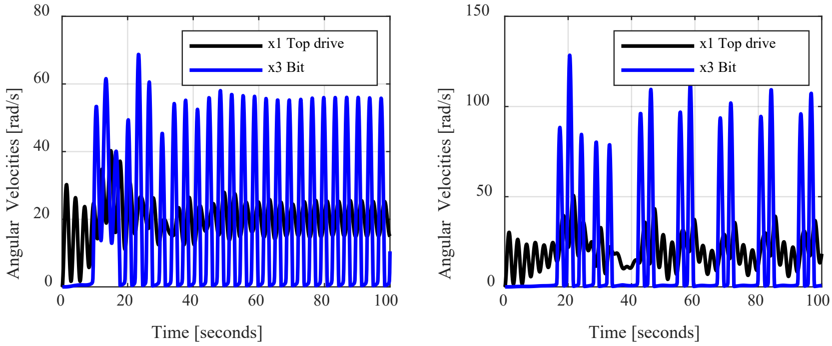


Figure 7

The angular velocities responses of the closed-loop rotary system on a drilling rig with PSO-PID control for: (a) Scenario 1.1, (b) Scenario 1.2, (c) Scenario 1.3, (d) Scenario 1.4, (e) Scenario 1.5, (f) Scenario 1.6

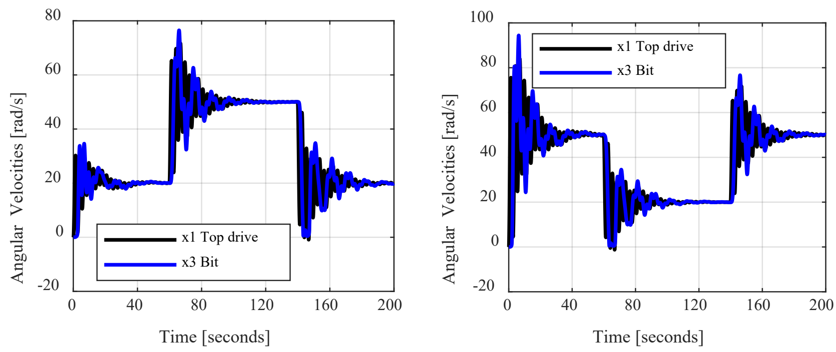
5.3.2 Scenario 2: Step-up and Step-down Input Reference

To evaluate the performance of the designed PSO-based PID controller against reference changes, various reference values were applied, and the used parameters are summarized in Table 5. Figures 8 depict the closed-loop step-up and step-down input reference responses of the rotary drilling system model, respectively. In both scenarios, the designed PSO-based PID controller demonstrated the ability to suppress the stick-slip vibration phenomenon and track the input reference signal, though with some transient oscillations due to the inherent system dynamics. The PSO-based PID controller effectively adapted to changes in the reference signal and maintained stable operation of the drilling rotary system. These results suggest that the PSO-based PID controller is a suitable control strategy for mitigating stick-slip vibrations and improving the overall performance of drilling operations. To confirm this finding, a comparative study was conducted, as detailed in the next subsection.

Table 5

Parameters for scenarios 2.1 and 2.2

Scenarios	Kp	Ki	Kd	Wob	Input type [Rad/s]		
					t<60	60≤t<140s	140≤t<200s
2.1	1.1722	0.3253	8.5164	120	20	50	20
2.2	1.1722	0.3253	8.5164	120	50	20	50



(a) (b)

Figure 8

The PSO-based PID Angular velocities of the top drive and the drill bit closed-loop responses to step-up signal (a) and step-down signal (b)

5.4 Comparative Analysis

The open-loop simulation results, depicted in Figure 4, revealed the presence of severe stick-slip vibrations in the drill string system. In this case, the drillers have to choose the appropriate Wob to ensure optimal drilling performance. This necessitated careful consideration to maintain drilling efficiency and avoid harmful damages associated with Wob-stimulated stick-slip vibrations. Thus, the compromise between the desired rate of penetration (ROP) and safe conditions without vibrations cannot be guaranteed.

To address and mitigate stick-slip vibrations while maintaining the desired rate of penetration, the effectiveness of a PID controller was investigated. As shown in Figure 5, the PID controller effectively reduced stick-slip vibrations. However, it exhibited a settling time exceeding 500 s and a significant steady-state error. To enhance the controller's performance, a PID controller with PSO tuning was implemented, resulting in a shorter settling time (less than 30 seconds) and no steady-state error (Figure 6). This improved controller stability during the drilling process. Moreover, the PSO-based PID controller's performance was then tested under various field-based scenarios. In optimal scenarios, the controller effectively Minimized stick-slip vibrations within an optimal time frame (Figure 7(a), (b), (c), and (d)). However, when the Wob was increased beyond the value (200 Nm), the controller struggled to suppress high-frequency stick-slip vibrations (Figures 7(e) and (f)).

Furthermore, the required angular velocity inputs became noisy and impractical for implementation in a top drive of an operational rotary drilling system in the field. The results demonstrated the effectiveness of the proposed controller in mitigating stick-slip vibration for both step-up and step-down scenarios (Figure 8).

These results establish the potential of the proposed control approaches for practical applications in the drilling industry with recommended Wob, emphasizing the importance of using advanced control techniques to enhance drilling performance and prevent equipment damage. Finally, in Figure 8, the Wob was set to its optimal value (100 Nm) for both step-up and step-down scenarios.

Conclusions

This study addressed the mitigation of stick-slip vibrations in rotary drilling systems, a persistent issue in the drilling industry that causes tool damage, reduced performance, and increased operational costs. The research utilized a PID controller optimized by the PSO algorithm, with the ITAE performance criterion as the fitness function. Simulation results demonstrated the effectiveness of this approach, achieving significant suppression of stick-slip vibrations in under 30 seconds, ensuring a stable and efficient drilling process.

The study also investigated the influence of the WOB on system performance, highlighting its critical role in vibration dynamics. The results showed that the proposed controller maintained robust performance under varying WOB conditions, effectively mitigating vibrations across a wide range of operational scenarios. This highlights the adaptability and reliability of the PSO-based PID controller in practical drilling applications.

Future research could focus on integrating artificial intelligence (AI) tools, such as machine learning or deep learning algorithms, to enhance the control and mitigation of stick-slip vibrations. AI-based approaches could enable predictive and adaptive control strategies, improving system robustness under dynamic and uncertain drilling conditions. Additionally, extending the PID controller design from an integer-order framework to a fractional-order one and exploring alternative tuning methodologies could further optimize vibration suppression performance.

This study underscores the practical potential of the proposed control approaches in the drilling industry. The demonstrated benefits, such as reduced drilling costs, improved system performance, and extended tool lifespan, illustrate the value of adopting advanced control techniques, including AI, to address the challenges posed by stick-slip vibrations and varying operational conditions, like WOB.

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