Stick-Slip Vibrations Control Strategy Design for Smart Rotary Drilling Systems

Mohamed Z. Doghmane[1(✉)], Abdelmoumen Bacetti[2], and Madjid Kidouche[1]

[1] Laboratory of Applied Automatic (LAA), Faculty of Hydrocarbons and Chemistry, M'hamed Bougara University, Boumerdes, Algeria
m.doghmanene@univ-boumerdes.dz

[2] Industrial Products Systems and Innovation Laboratory (IPSIL), National Polytechnic School of Oran (ENPO), Oran, Algeria

Abstract. The objective of this paper is to design new strategy using three controllers for rotary drilling systems located in Algerian oil field. Torsional vibration is one of the most challenges facing petroleum drilling technology, it creates the stick- slip phenomenon that decreases Borehole quality, increases drilling cost through additional operations, and reduces penetration rate. The controllers are designed to minimize the vibrations so that maximize penetration rate and decreases drilling operation costs through avoiding unnecessary operations such as side track. The simulations results were so promising; thus a 3D prototype of rotary drilling systems has been realized in laboratory to validate the proposed approaches. Moreover, a graphical interface has been created to facilitate the use of this strategy by drilling field supervisors.

Keywords: Control strategy · Rotary drilling system · Torsional vibrations · Stick-Slip phenomenon · Side track · 3D prototype

1 Introduction

Petroleum industry has played a major role in the Algerian economy for the last few years, wherein many researchers have focused on problematic of production costs optimization regarding the increased need of this source of energy. Since drilling system is one of the most expensive parts of petroleum production industry, therefore, a deep study of new optimization control strategy is very important for efficient production capacities increase. Rotary drilling system is designed by combining mechanical and electrical subsystems for the purpose of drilling a well, the mechanical part of the system can be simply seen as a beam rotating at constant speed and in its limits drills with drill bit [1]. The stick-slip phenomenon appears under certain circumstances; sudden change of rock hardness stops the drill bit and creates the stick phase, then the drill bit is released and starts again with speed higher than the drill string surface speed and it creates slip phase [2]. Consequently, these two phases generate torsional vibrations along the drill string. It has been noticed in the drilling field that the torsional vibrations have many effects on drill string equipment, the drilling system damage is subject to high couple created, and it also imposes very

M. Hatti (Ed.): ICAIRES 2020, LNNS 174, pp. 197–209, 2021.
https://doi.org/10.1007/978-3-030-63846-7_20

expensive extra operations to deal with the low quality of the borehole. Moreover, the performance of drilling process is decreased in term of capacity due to postponing axial advancement [3]. Many researchers have interested in decreasing the 'Stick-slip' phenomenon effects using different types of controllers ([4–7]). However, most of these works are based on simplified mathematical model of the rotary drilling system and no experimental validations have been realized [8]; we can find also that proportional integral (PI) controller in used in [9], H infinity controller in ([10, 11]), and sliding mode controller in [12]. On the other side, few researchers have taken the generalized nonlinear model of the system in consideration to deal with this phenomenon, wherefore; no control strategy is applied in rotary drilling system of oil field industry. For these reasons, this paper takes the objective of designing strategy using PI, PID, and Hinfinity controllers for the generalized nonlinear model of the rotary drilling system. In order to experimentally validate this strategy, a prototype of rotary drilling system has been designed in the laboratory.

2 Mathematical Model of Rotary Drilling System

The mathematical model proposed in this paper is the generalized model of n elements; the special cases of this model converges to models used in [8], and in [11]. In this study we consider that the drill-string behaves as a torsional pendulum, i.e. the drill pipes are represented by torsional spring, the drill collar behaves as a rigid body and the top drive rotates at constant speed (Fig. 1). The inertial masses J_p and J_b, locally damped by d_p and d_b, are connected one to each other by a linear spring with torsional stiffness k and torsional damping μ [13]. The equations of motion can be represented as follows

$$\begin{cases} J_p\ddot{\theta}_p + d_p\left(\dot{\theta}_p - \dot{\theta}_b\right) + k\left(\theta_p - \theta_b\right) + \mu_p\dot{\theta}_p = u_T \\ J_b\ddot{\theta}_b - d_b\left(\dot{\theta}_p - \dot{\theta}_b\right) - k\left(\theta_p - \theta_b\right) + \mu\dot{\theta}_b = Tob\left(\dot{\theta}_b\right) \end{cases} \quad (1)$$

$\theta_p, \theta_b, u_T,$ and $Tob\left(\dot{\theta}_b\right)$ are the angular displacements of the top drive and of the BHA respectively. The control signal u_T is the drive torque coming from the top drive, transmission box used to regulate the rotary angular velocity $\dot{\theta}_b$. The frictional torque T represents the torque on bit and the nonlinear frictional forces along the drill collars [14]. The rotary drilling system is composed of N_s string elements ($i = 1 \cdots N_s$). For $i = 1$

$$J_1\ddot{\theta}_1 = T_1 - T_2 - \mu\dot{\theta}_1 \text{ with } T_1 = d_1\left(\dot{\theta}_{td} - \dot{\theta}_1\right) + K_1(\theta_{td} - \theta_1) \quad (2)$$

For $i = 2 \cdots N_s - 1$

$$J_i\ddot{\theta}_i = T_i - T_{i+1} - \mu\dot{\theta}_i \text{ with } T_i = d_i\left(\dot{\theta}_{i-1} - \dot{\theta}_i\right) + K_i(\theta_{i-1} - \theta_i) \tag{3}$$

For $i = N_s$

$$J_{N_s}\ddot{\theta}_{N_s} = T_{N_s} - (\mu + \mu_b)\dot{\theta}_{N_s} \text{ with } T_{N_s} = d_{N_s}\left(\dot{\theta}_{N_s-1} - \dot{\theta}_{N_s}\right) + K_{N_s}(\theta_{N_s-1} - \theta_{N_s}) \tag{4}$$

If we put $\dot{\theta}_1 = x_1$,$\theta_i = x_i$, $i = 2 \cdots N_s - 1$,$\dot{\theta}_{td} = u$,$\theta_{td} - \theta_{N_s} = x_{N_s+1}$, and $\theta_j - \theta_{j+1} = x_{N_s+j+1}$, $j = 1 \cdots N_s - 1$ we can find the extended model of equations as follows:
For $i = 1$

$$\dot{x}_1 = -\frac{(d_1 + d_2 + \mu)}{J_1}x_1 + \frac{d_2}{J_1}x_2 + \frac{K_1}{J_1}x_{N_s+1} - \frac{K_2}{J_1}x_{N_s+2} + \frac{d_1}{J_1}u \tag{5}$$

For $i = 2 \cdots N_s - 1$

$$\dot{x}_i = \frac{d_i}{J_i}x_{i-1} - \frac{(d_i + d_{i+1} + \mu)}{J_i}x_i + \frac{d_{i+1}}{J_i}x_{i+1} + \frac{K_i}{J_i}x_{N_s+i} - \frac{K_{i+1}}{J_i}x_{N_s+i+1} \tag{6}$$

For $i = N_s$

$$\dot{x}_{N_s} = \frac{d_{N_s}}{J_{N_s}}x_{N_s-1} - \frac{(d_{N_s} + \mu + \mu_b)}{J_{N_s}}x_{N_s} + \frac{K_{N_s}}{J_{N_s}}x_{2N_s} \tag{7}$$

For $i = N_s + 1$

$$\dot{x}_i = u - x_1 \tag{8}$$

For $i = N_s + 2 \cdots 2N_s$ we have

$$\dot{x}_i = x_{i-N_s-1} - x_{i-N_s} \tag{9}$$

If we put $N_s = 4$ we obtain the reduced system as below

$$\left\{\begin{array}{c} \dot{x}_1 = -\frac{(d_1+d_2+\mu)}{J_1}x_1 + \frac{d_2}{J_1}x_2 + \frac{K_1}{J_1}x_5 - \frac{K_2}{J_1}x_6 + \frac{d_1}{J_1}u,\ i = 1 \\ \dot{x}_i = \frac{d_i}{J_i}x_{i-1} - \frac{(d_i+d_{i+1}+\mu)}{J_i}x_i + \frac{d_{i+1}}{J_i}x_{i+1} + \frac{K_i}{J_i}x_{i+4} - \frac{K_{i+1}}{J_i}x_{i+5},\ i = 2,3 \\ \dot{x}_4 = \frac{d_4}{J_4}x_3 - \frac{(d_4+\mu+\mu_b)}{J_4}x_4 + \frac{K_4}{J_4}x_8,\ i = 4 \\ \dot{x}_i = u - x_1,\ i = 5 \\ \dot{x}_i = x_{i-N_s-1} - x_{i-N_s},\ i = 6 \cdots 8 \end{array}\right. \tag{10}$$

3 Controllers Design for General Model

A state space model of the drill-string torsional behavior can be derived from (11) as

$$\begin{cases} \dot{X} = AX + Bu + Ed \\ Y = CX \end{cases} \tag{11}$$

Where $X = \begin{pmatrix} \dot{\theta}_1 & \dot{\theta}_2 & \cdots & \dot{\theta}_{2N_s} \end{pmatrix}^T$ is the state vector, $Y = \begin{pmatrix} \dot{\theta}_1 & \dot{\theta}_{N_s} \end{pmatrix}^T$ is the output vector, $\left(u = \dot{\theta}_1\right)$ is the top drive input velocity, $(d = Tob)$ is the known/measured input torque-on-bit. C and E are known matrices with appropriate dimensions [15].

$$\begin{cases} E = \begin{pmatrix} 0 & 0 & 0 & -1/J_4 & 0 & 0 & 0 & 0 \end{pmatrix}^T \\ C = \begin{pmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix}^T \end{cases} \tag{12}$$

The error is added in order to achieve some desired robustness performance.

3.1 Conventional PI, PID Controllers

Conventional PI (or PID) control is an implementation of error-based feedback control; its fundamental theory is very simple. Suppose that $y_r(t)$ is the set of reference input, and $y(t)$ is the real output of the system. Then the error is $e(t) = y(t) - y_r(t)$, and the classical PID control input is defined as follows

$$u(t) = -a_0 \int_{t_0}^{t} (y(\tau) - y_r(\tau))d\tau - a_1(y(t) - y_r(t)) - a_2 \frac{d}{dt}(y(t) - y_r(t)) \tag{13}$$

Where $a_0, a_1,$ and a_2 are the design parameters, they are called integral, proportional, and derivative gains respectively [16]. PI controller Eq. (17) can be reduced into

$$u(t) = -a_0 \int_{t_0}^{t} (y(\tau) - y_r(\tau))d\tau - a_1(y(t) - y_r(t)) \tag{14}$$

3.2 Improved Ziegler-Nichols Tuning

The classical tuning rules have been widely used in industrial systems, however, the obtained control system lacks of robustness especially for system with fast dynamic [17]. For this reason, an improved Ziegler-Nichols tuning process has been chosen, the process is obtained by fitting the model

$$P(s) = \frac{a_0}{1 + sT} e^{-sT_d} \tag{15}$$

The process steady state gain K is found from the steady state value of the step response [16].

3.3 H Infinity Controller

The mathematical model of the system given in Eq. (10) is written as

$$\begin{cases} \dot{x}(t) = Ax + Bu \\ y(t) = Cx \end{cases} \quad (16)$$

A more general state space representation of the system is given as follows

$$\begin{cases} \dot{x}(t) = Ax(t) + B_1\omega(t) + B_2W(t) \\ z(t) = C_1x(t) + D_{11}\omega(t) \\ y(t) = C_2x(t) + D_{21}\omega(t) \end{cases} \quad (17)$$

Where the matrix form of Eq. (21) is given as

$$\begin{bmatrix} \dot{x}(t) \\ z(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & 0 \\ C_2 & D_{21} & 0 \end{bmatrix} \cdot \begin{bmatrix} x(t) \\ w(t) \\ u(t) \end{bmatrix} = P \quad (18)$$

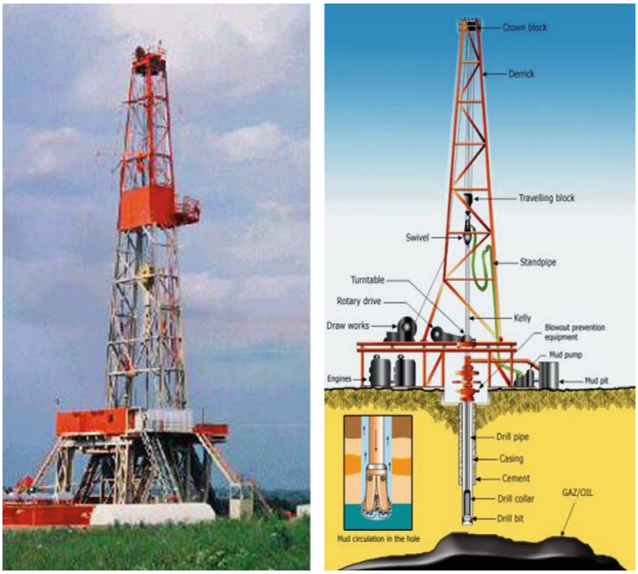
The solution of this H_∞ problem in Eq. (22) based on Riccati equations is implemented and the following conditions are verified

- A, B_2 is stabilisable and C_2, A is detectable,
- D_{12} and D_{21} have full rank,
- $A - jwI$, B_2, C_1, D_{12} has full column rank for all w_R hence,D_{12} is tall,
- $A - jwI$, B_1, C_2, D_{21} has full column rank for all w_R hence, D_{21} is wide.

The expended model is produced by accounting for the weighting functions $W_1, W_2,$ and W_3. To reach best control robustness, the outputs were chosen to be transfer weight functions as:$z_1 = W_1 * e$; $z_2 = W_2 * u$; $z_3 = W_3 * y$ [18].
The cost function of mixed sensibility is given for

$$T_{y1u1} = \begin{bmatrix} W_1S \\ W_2R \\ W_3T \end{bmatrix}, \quad S = (I + GK)^{-1}, \quad R = K(I + GK)^{-1}, \quad T = GK(I + GK)^{-1} \quad (19)$$

Where S and T are called sensibility and complementary sensitivity functions respectively. The transfer function from W to z_1 is the weighted sensitivity function W_{1S}, which characterizes the performance objective of good tracking; the transfer function from W to z_2 is the complementary sensitivity function T, whose minimization ensures low control gains at high frequencies, and the transfer function from W to z_3 is K_s, which measures the control effort. It is also used to impose the constraints on the control input [18].



(a) (b)

Fig. 1. Rotary drilling system: **a)** Image of real system, **b)** Detailed schematic diagram

4 Results and Discussion

4.1 Simulation Results

Parameters used in this study are summarized in Table 1.

Table 1. Parameters used in rotary drilling system mathematical model

Parameters	Definition	Value
D_{bit}	bit diameter	0.2159 m
k_b	Boussaada's simplified model coefficient	0.3
OD_s	outer diameter of the string pipe	0.127 m
ID_s	inner diameter of the string pipe	0.1086 m
L_{sp}	length of one string pipe	9.14 m
N_{sp}	number of string pipes	383
Y_{sp}	Young modulus of string pipes	200*1e9
G_{sp}	Shear modulus of string pipes	79.3*1e9
P_{sp}	Poisson's ratio of string pipes	0.3
RHO_{sp}	density of string pipes material	7850
$ODbh_a$	outer diameter of the BHA	0.1651 m
ID_{bha}	inner diameter of the BHA	0.0714 m
L_{bhap}	length of one BHA pipe	9.14 m
N_{bhap}	number of BHA pipes	22

(*continued*)

Table 1. (*continued*)

Parameters	Definition	Value
Y_{bhap}	Young modulus of BHA pipes	200*1e9
G_{bhap}	Shear modulus of BHA pipes	79.3*1e9
P_{bhap}	Poisson's ratio of BHA pipes	0.3
RHO_{bhap}	density of BHA pipes material	7850
Nes	number of elements of the drill string	10
Nebha	number of elements of the BHA	4

The parameters of the generalized model have been calculated using basic equations ([19], [20]) as follows
Number of elements

$$N_e = N_{es} + N_{ebha} \tag{20}$$

Length of one string element

$$L_{es} = N_{sp} * L_{sp}/N_{es} \tag{21}$$

Length of one BHA element

$$L_{ebha} = N_{bhap} * L_{bhap}/N_{ebha} \tag{22}$$

Drilling depth

$$D_{epth} = \left(N_{sp} * L_{sp}\right) + \left(N_{bhap} * Lbhap\right) \tag{23}$$

Moment of Inertia
For string elements

$$J_{es} = \pi * RHO_{sp} * L_{es} * \left(OD_s^4 - ID_s^4\right)/32 \tag{24}$$

For BHA

$$J_{ebha} = \pi * RHO_{bhap} * L_{ebha} * \left(OD_{bha}^4 - ID_{bha}^4\right)/32 \tag{25}$$

$$J_{eff} = \left(4 * J_{es}/\left(\pi^2\right)\right) + J_{ebha} \tag{26}$$

Stiffness coefficients vector

$$K_{es} = G_{sp} * \pi * \left(OD_{bha}^4 - ID_{bha}^4\right)/(32 * L_{es}) \tag{27}$$

$$K_{ebha} = G_{bhap} * \pi * \left(OD_{bha}^4 - ID_{bha}^4\right)/(32 * L_{ebha}) \tag{28}$$

Mass

$$M_{es} = RHO_{sp} * L_{es} * \pi * \left(OD_s^2 - ID_s^2\right)/4 \quad (29)$$

$$M_{ebha} = RHO_{bhap} * L_{ebha} * \pi * \left(OD_{bha}^2 - ID_{bha}^2\right)/4 \quad (30)$$

Axial Spring constant

$$S_{es} = Y_{sp} * \pi * \left(OD_s^2 - ID_s^2\right)/(4 * L_{es}) \quad (31)$$

$$S_{ebha} = Y_{bhap} * \pi * \left(OD_{bha}^2 - ID_{bha}^2\right)/(4 * L_{ebha}) \quad (32)$$

Dynamic Viscosity coefficient

$$ETA_{es} = (Ses * J_{es}/(M_{es} * K_{es}))^{1/2} \quad (33)$$

$$ETA_{ebha} = (Sebha * J_{ebha}/(M_{ebha} * K_{ebha}))^{1/2} \quad (34)$$

Damping coefficients vector

$$d_{es} = 30 * L_{es} * D_{bit}^2 * OD_s^2 * ETA_{es}/\left(D_{bit}^2 - OD_s^2\right) \quad (35)$$

$$d_{ebha} = 30 * L_{ebha} * D_{bit}^2 * OD_{bha}^2 * ETA_{ebha}/\left(D_{bit}^2 - OD_{bha}^2\right) \quad (36)$$

Torque on bit

$$Tob = (2 * k_b * x_{N_s})/\left(k_b^2 + x_{N_s}^2\right) + \left(\left(1/\left(\left(\left(x_{N_s}^2 + O_0^2\right)^{1/2}\right)\right)\right) + \left((p * O_0)/\left(\left(x_{N_s}^2\right) + \left(O_O^2\right)\right)\right)\right) - ((x_{Ns})/O_1 - 1) \quad (37)$$

Simulation results of the designed controller are show in Fig. 2

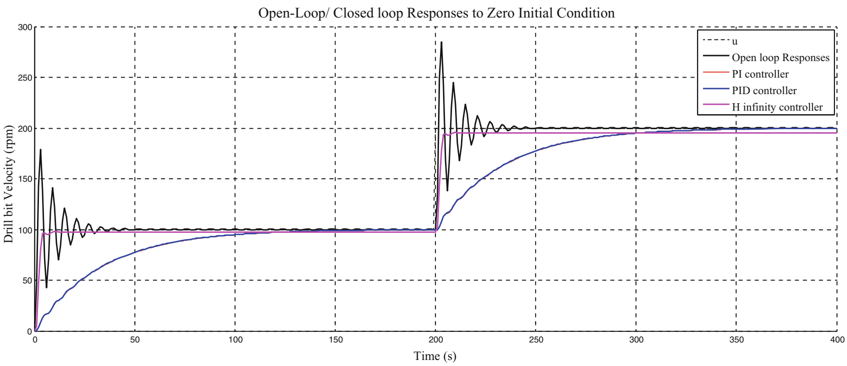


Fig. 2. Open loop, closed loop responses for PI, PID, and Hinfinity controllers – linearized model

4.2 Experimental Results of the Drilling System Prototype

A graphical user interface has been developed (Fig. 3) and implemented with DSpace interface so that it can facilitate the controllers manipulations of prototype system.

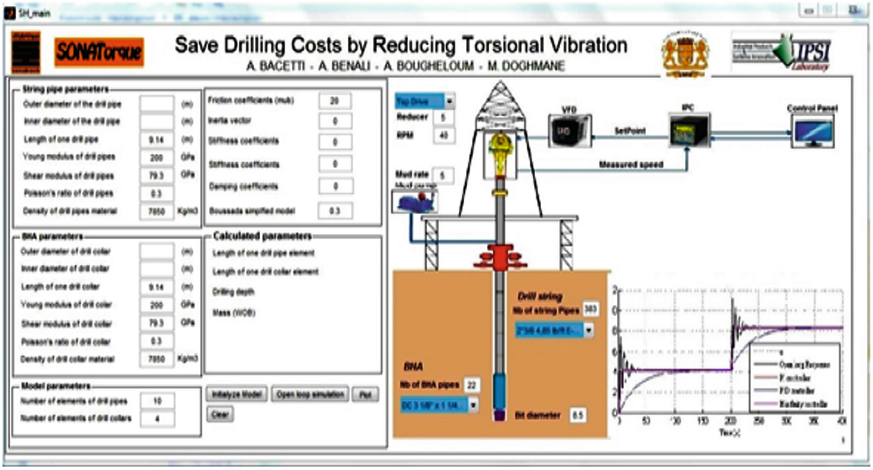
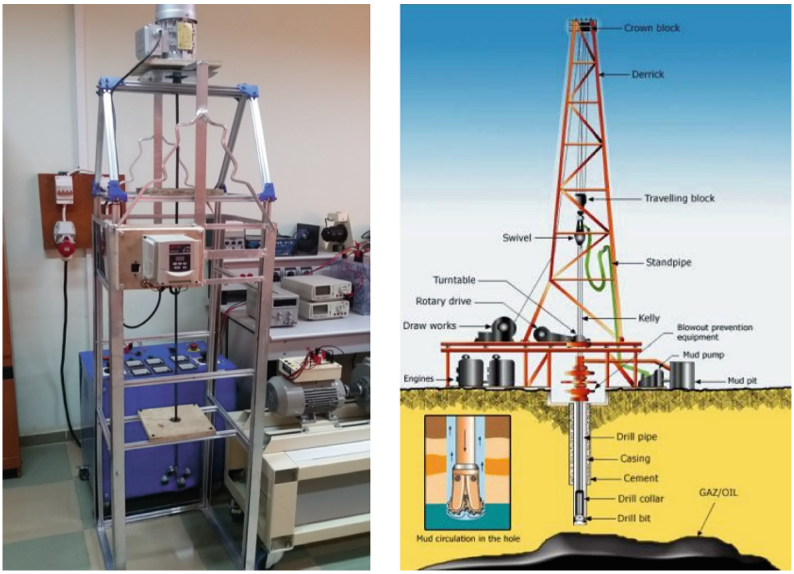


Fig. 3. Graphical user interface for the developed control strategy

The dimensions of rotary drilling shown in Fig. 4. A have been reduced by keeping the proportionality between them (Fig. 4.B).



(a) (b)

Fig. 4. Rotary drilling system; a) Image of realized prototype, b) Detailed schematic diagram

The torque on bit of the prototype has been given in Fig. 5; it is stabilized at 8 T after 160 s.

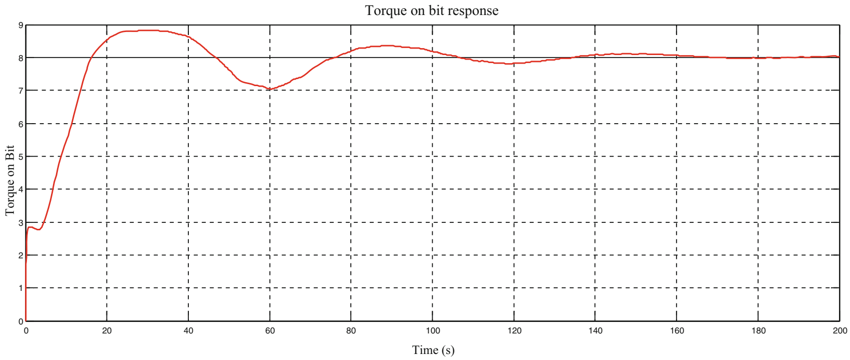


Fig. 5. Torque on bit response of the nonlinear model of the system

The open loop responses for five elements model are shown in Fig. 6 where it is noticed that this responses are stabilized after 160 s also, the torsional vibrations have affected the velocity responses in the interval [0 160 s]. It is also noticed that element 3 has the highest velocity response value (Fig. 6), where it has the most remarkable vibration effect, it can be interpreted as the most risky point of drill string damage.

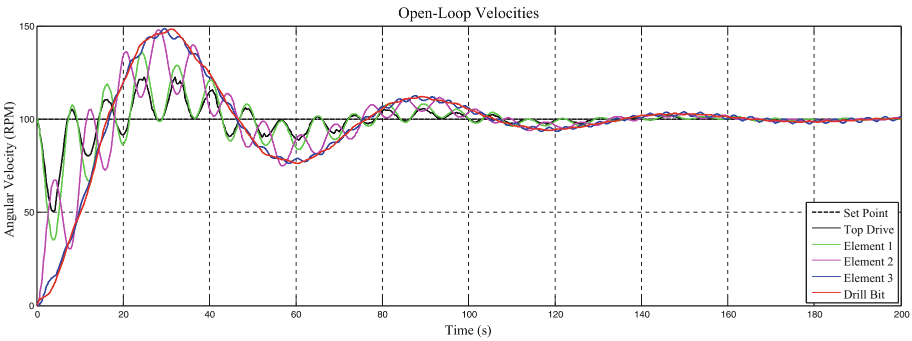


Fig. 6. Five elements responses of the nonlinear model of the system

In order to generalize the designed algorithm, many input references have been used (Figs. 7, 8, and 9); these signals can represent any type of input signals in oil field drilling system. As it is shown in Figs. 7, 8, and 9 the controller have tracked different types of input signals, where it is noticed that PI and PID controllers give the same tracking performances. However, Hinfinity controller offered a better tracking performance with better minimization of torsional vibration and time response, it can be considered as the best solution in the status of stuck or slip phases, however it can reduce the axial advancement, thus a switch between PI (unfavorably derivative term) and Hinfinity controllers will increase the efficiency of control tasks; PI controller in normal situation without any vibrations, as soon as there is stuck of drill bit automatic switch to Hinfinity controller is done, when the drill bit speed return near to the drill string surface speed an automatic switch back to PI controller is done and so on.

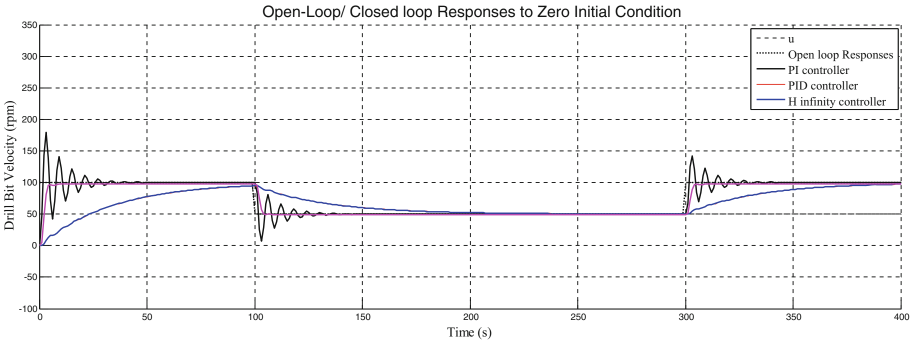


Fig. 7. Response of the nonlinear system with second type of top drive velocity input

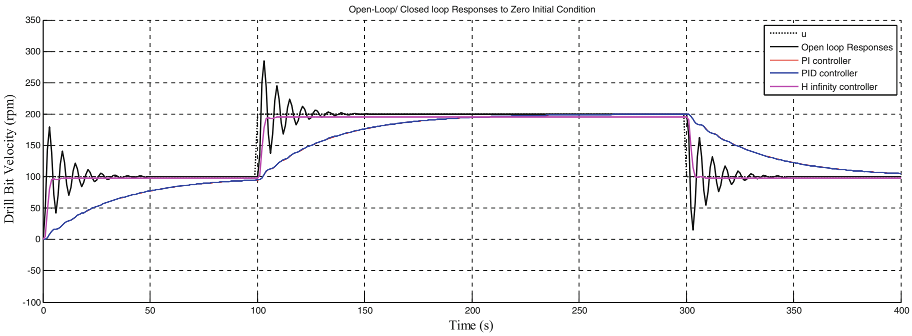


Fig. 8. Result of nonlinear system with third type of top drive velocity input

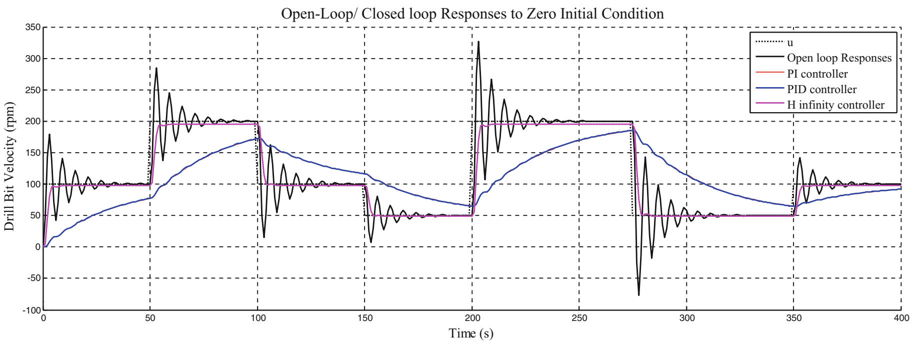


Fig. 9. Result of the nonlinear system with fourth type of top drive velocity input

5 Conclusion

This study dealt with the design of control strategy for the purpose of controlling torsional vibrations in rotary drilling system, the strategy is based on PI, PID, and Hinfinity controllers' responses; it combines these controllers to have desired maximum system performance with minimum drill string vibrations. The promising simulation results guided us to design, experimentally, a prototype of rotary drilling system, it gave the opportunity to validate the proposed algorithms, thus propose the implement of the developed strategy to an operating Algerian drilling system so that extra drilling cost can be avoided.

References

1. Saldivar, B.: Analysis, modeling and control of an oil well drilling system. Cotutelle Ph.D. Thesis. Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional, Mexico. Institut de Recherche en Communications et Cybernétique de Nantes, France (2013)
2. Lear, W., Dareing, D.: Effect of drill string vibrations on MWD pressure pulse signals. J. Energy Res. Technol. **112**(2), 84–89 (1990)
3. Saldivar, B., Mondié, S.: Drilling vibration reduction via attractive ellipsoid method. J. Franklin Institute Elsevier **350**(3), 485–502 (2013)
4. Zhu, X., Tang, L., Yang, Q.: A literature review of approaches for stick-slip vibration suppression in oil well drill string. Adv. Mech. Eng. **6**, 967952 (2014)
5. Karkoub, M., Abdel-Magid, Y.L., Balachandran, B.: Drill string torsional vibration suppression using GA optimized controllers. J. Canad. Petroleum Technol. **48**(12), 32–38 (2009)
6. Puebla, H., Alvarez-Ramirez, J.: Suppression of Stick-Slip in Drill strings: A Control Approach Based on Modeling Error Compensation. J. Sound Vib. **310**(4–5), 881–901 (2008)
7. Richard, T., Germay, C., Detournay, E.: A simplified model to explore the root cause of stick slip vibrations in drilling systems with drag bits. J. Sound Vib. **305**, 432–456 (2007)
8. Fubin, S., Linxiu, S., Lin, L., Qizhi, Z.: Adaptive PID control of rotary drilling system with stick slip oscillation. In: The 2nd International Conference on Signal Processing Systems, ICSPS 2010. pp. 289–292 (2010)
9. Serrarens, A.F.A., van de Molengraft, M.J.G., Kok, J.J., van den Steen, L.: H∞ Control for Supressing Stick-Slip in Oil Well Drillstrings. IEEE Control Syst. Magaz. **18**(2), 19–30 (1998)
10. Hernández-Suárez, R., Puebla, H., Aguilar-López, R., Hernández-Martínez, E.: An integral high-order sliding mode control approach for stick-slip suppression in oil drill strings. Petrol. Sci. Technol. **27**(8), 788–800 (2009)
11. Liao, C., Balachandran, B., Karkoub, M., Abdel-Magid, Y.L.: Drill-string dynamics: reduced-order models and experimental studies. J. Vib. Acoust. **133**(4), 8 (2011). 041008
12. Kessai, I., Benammar, S., Doghmane, M.Z., Tee, K.F.: Drill bit deformations in rotary drilling systems under large-amplitude stick-slip vibrations. Appl. Sci. **10**, 6523 (2020)
13. Li, Z., Gaob, H., Agarwalc, R., Kaynakd, O.: H∞ control of switched delayed systems with average dwell time. Int. J. Control **86**(12), 2146–2158 (2013)
14. Germay, C., Van De Wouw, N., Nijmeijer, H., Sepulchre, R.: Nonlinear drilling dynamics analysis. SIAM J. Appl. Dynamical Syst. **8**(2), 527–553 (2005)

15. Navarro-López, E.: An alternative characterization of bit-sticking phenomena in a multi-degree-of-freedom controlled drill string. Nonlinear Anal. Real World Appl. **10**(5), 3162–3174 (2009)
16. Riane, R., Kidouche, M., Illoul, R., Doghmane M. Z.: Unknown Resistive torque estimation of a rotary drilling system based on kalman filter. IETE J. Res. (2020) https://doi.org/10.1080/03772063.2020.1724834
17. Doghmane, M. Z., Kidouche, M., Habbi, H., et al.: A new decomposition strategy approach applied for a multi-stage printing system control optimization. In: 4th International Conference on Electrical Engineering (ICEE), Boumerdes, Algeria, (2015)
18. Mendil, C., Kidouche, M., Doghmane, M. Z.: Automatic control of a heat exchanger in a nuclear power station: The classical and the fuzzy methods. In: IEEE International Conference on Advanced Electrical Engineering (ICAEE), 19–21 Nov. 2019, Algiers-Algeria (2019) https://doi.org/10.1109/icaee47123.2019.9014661
19. Doghmane, M.Z., Kidouche, M.: Decentralized controller Robustness improvement using longitudinal overlapping decomposition- Application to web winding system. Elektronika ir Elektronika **24**(5), 10–18 (2018). https://doi.org/10.5755/j01.eie.24.5.21837
20. Riane, R., Kidouche, M., Doghmane, M.Z., Illoul, R.: Modeling of torsional vibrations dynamic in drill-string by using PI-observer. In: Bououden, S., Chadli, M., Ziani, S., Zelinka, I. (eds.) Proceedings of the 4th International Conference on Electrical Engineering and Control Applications. ICEECA 2019. Lecture Notes in Electrical Engineering, vol. 682. Springer, Singapore (2021). https://doi.org/10.1007/978-981-15-6403-1_12