PAPER • OPEN ACCESS

Feasibility study of nonlinear model predictive control in mitigating stick slip in drilling

To cite this article: Xueying Wang *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **621** 012150

View the article online for updates and enhancements.

Feasibility study of nonlinear model predictive control in mitigating stick slip in drilling

Xueying Wang[1, 2*], Hongjian Ni[1, 2] and Ruihe Wang[1, 2]

[1]Key Laboratory of Unconventional Oil & Gas Development (China University of Petroleum (East China)), Ministry of Education, Qingdao 266580, P. R. China

[2]School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, P. R. China

*Corresponding author's e-mail: b16020048@s.upc.edu.cn

Abstract. Drilling is an essential and expensive process to extract conventional and unconventional underground resources, like oil, natural gas and geotherm. Stick slip is one of the problems involved in rotary drilling that cause inefficiency and premature downhole tool failures. This work investigates the feasibility of using nonlinear model predictive control (NMPC) in mitigating stick slip. To make real-time control possible, a new balanced truncation method is used to reduce system order, and advanced step NMPC method is used to remove computational delay. Simulation results demonstrate that the proposed NMPC method can run in real time and eliminate stick slip. Compared to the advanced ZTorque controller, slight to moderate torsional vibrations still occur in the NMPC. The competitive advantage of the NMPC is that it does not need high-frequency drill pipe torque measurement.

1. Introduction

Drilling is an essential process to construct a channel and extract underground resources, like oil, natural gas and geotherm. Generally, the well's depth is up to thousands of meters. In such a wellbore, stick slip often happens when drill string is rotating. Stick slip is a term to describe the process in which a drill bit is stationary for a while (stick phase) and then sharply rotates (slip phase) in large revolutions per minute (RPM). Stick slip not only reduces drilling rate of penetration (ROP), but also damages downhole drill tools, like drill bits and mud motors.

A few commercial controllers have been developed to mitigate stick slip, including Soft Torque, Soft Speed and recently developed ZTorque. Torsional wave propagates from downhole to top drive. In the usual case, top drive behaves like a stiff boundary, and few of vibration energy is absorbed. The controllers work by reducing the reflection coefficient at the top drive.

Soft Torque and Soft Speed are designed based on classical vibration theory of two freedoms system[1]. In these controllers, thin-wall drill pipe is modelled as a massless spring, and thick-wall drill collar is modelled as a rigid mass. Top drive provides another freedom. Jansen proposed a method to design top drive equivalent stiffness and damping coefficients, and these optimized parameters make sure vibration decay in the fastest speed[2]. However, drilling mud damping and drill bit/rock interaction may largely alter the system properties. Additionally, the accuracy of modelling a long drill string as a spring/mass declines as well's depth increases. Therefore, parameter tuning is needed for Soft Torque and Soft Speed controllers.

ZTorque is developed to remove the parameter tuning process of Soft Torque and Soft Speed[3]. ZTorque controller is also called impedance matching controller. ZTorque controller adjusts top drive rotary speed to make the top drive mechanical impedance equal to that of drill pipe connected to top drive. During perfect impedance matching, 100% of wave energy from the bit is transmitted across the top drive and none is reflected.

The aforementioned controllers can usually deliver a good performance, but they are not always turned on for some top drives installed these software packages. Because the controllers require high-frequency accurate torque measurement.

Model predictive control (MPC) uses the process dynamics to optimize control inputs, and has the ability to contain many constraints in the model. NMPC has been successfully used in drilling industry, like managed pressure drilling[4]. Johannessen and Myrvold[5] studied the feasibility of NMPC in mitigating stick slip in vertical wells. In this paper, NMPC is used to mitigate stick slip in horizontal wells. A new balanced truncation method and advanced step NMPC method[6] (asNMPC) are used to reduce model scale and remove computational delay.

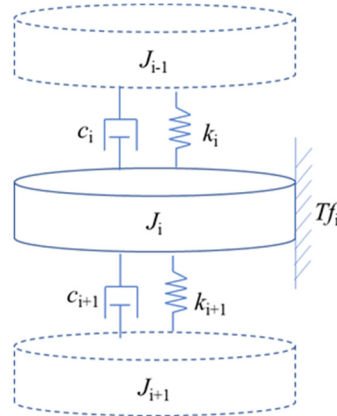## 2. Methods

2.1 Drill string model

Figure 1. Mass-spring-damper equivalent system of a drill string

As shown in Figure 1, drill string is modelled as a n degrees of freedom (DOF) mass-spring-damping system. The value of n is dependent on well's depth. Only movement in the torsional direction is considered. For i-th element, the dynamics equation is as follows,

$$J_i \ddot{\varphi}_i = -k_{i-1}(\varphi_i - \varphi_{i-1}) - k_i(\varphi_i - \varphi_{i+1}) - c_i \dot{\varphi}_i - Tf_i \tag{1}$$

$$Tf_i = Fc_i \frac{Do_i}{2} \mu_i \tag{2}$$

where J is the drill string inertia; φ is the angular displacement; k is the equivalent torsion stiffness; c is the equivalent linearized drilling mud damping; Tf is the frictional torque; Fc is the contact force between the wellbore and the drill string; Do is the drill string equivalent outer diameter; μ is the friction coefficient.

A velocity-dependent friction model as shown in Equation (3) is used,

$$\mu = \begin{cases} \mu_s & |v_r| \le D_v \\ \mu_s + (\mu_s - \mu_d)\,e^{-((v_r - D_v)/v_s)} & |v_r| > D_v \end{cases} \tag{3}$$

where μ_s and μ_d are the static and dynamic friction coefficient, respectively. v_r is the velocity of contact point. D_v and v_s are two constants.

The top drive is actuated by a motor torque, T_m, controlled by a PI controller, also known as a stiff PI controller, to a desired velocity set-point ω_{sp};

$$e = \omega_{sp} - \omega_{TD}, \ I_e = \int_0^t e(t)dt, \ T_m = k_p e + k_i I_e \tag{4}$$

The top drive dynamics equation is as follows,

$$\frac{\partial \omega_{TD}}{\partial t} = \frac{1}{J_{TD}}(T_m - T_0) \tag{5}$$

where T_0 is the torque at the top of drill string, and J_{TD} is the inertia of the top drive.

As for bit boundary, the following equation is used to describe the relation between bit velocity, ω_b and torque on bit, T_b,

$$T_b = \begin{cases} T_{bc}, & |\omega_b| \le \omega_{bc} \\ \dfrac{a_1}{|\omega_b|} + a_2|\omega_b| + a_3, & |\omega_b| > \omega_{bc} \end{cases} \tag{6}$$

where is a_1, a_2, a_3 and ω_{bc} four constant parameters.

One big challenge of NMPC in mitigating stick slip is the computational time cost. To make online optimization possible, the drill string model has to be reduced. A new balanced truncation method combined with dominance theory has been developed for model reduction of non-equilibrium behaviors [7], and this method is able to find a reduced model that still contains the most important dynamics found in the original system, in other words, keeping the input-output behavior. The detailed algorithm consisting of two parts can be found in [7], and they are not included in this paper for simplicity.

2.2 NMPC formulation
The basic idea of linear or nonlinear MPC is to minimize an objective function to find optimal control inputs. For stick slip mitigation problem, the objective function is as follows,

$$\min_u \Phi = (\omega_b - \omega_{bt})^T W_b (\omega_b - \omega_{bt}) + (\omega_{TD} - \omega_{SP})^T W_{td} (\omega_{TD} - \omega_{SP}) \tag{7}$$

where u is the manipulated variable, in this case, it represents top drive rotary velocity; ω_{bt} is target bit rotary velocity; W_b and W_{td} are two weighting matrices.

The objective function is to maintain a desired rotary speed and at the same time to remove stick slip. For the NMPC, the direct control input is top drive rotary velocity, and a cascade control is therefore needed to calculate the corresponding top drive torque input to maintain such a rotary velocity input.

There are two parameters needed to be tuned in the NMPC, namely prediction horizon, *hp*, and control horizon, *hc*. *hp* determines how long the prediction simulation covers, and *hc* determines how many control steps are included in the specified horizon *hor*.

Although the reduced model can accelerate the optimization process, computational time delay still exists. asNMPC is used to solve this problem. The main idea is to use the current control action to predict the future states, and then solve the future optimization problem in advance[6]. In the nominal case, the prediction matches the future states so that the current solution is already available, thus avoiding the computational delay. A sensitivity based algorithm is adopted to achieve asNMPC, and more details can be found in [6], and not repeated here for simplicity.

2.3 ZTorque controller
In order to evaluate the performance of the NMPC controller, the most advanced ZTorque controller is presented here as a comparison.

The control diagram for a ZTorque system is shown in Figure 2. It is still a PI controller, but with a term related to torque fluctuation filtered by a low pass filter and a high pass filter.
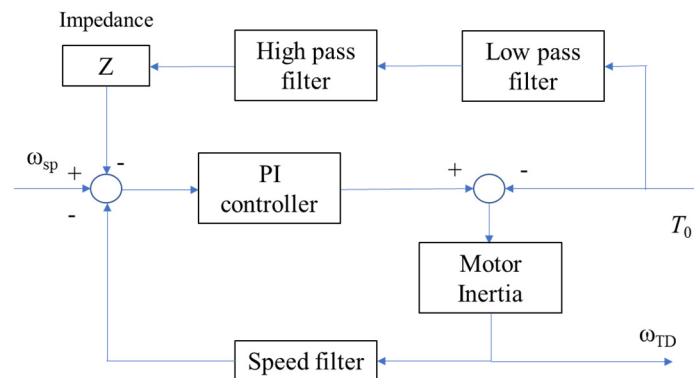
Figure 2. Control diagram for a ZTorque system

3. Simulation results and discussions

In this section, the performance of the NMPC controller is presented, and the performance of ZTorque controller is also presented for comparison. The controllers are examined against two horizontal well profiles, one with a depth of 3600 m, and the other with a depth of 5600 m.

Figure 3 shows the step response of the stiff PI controller in a 3600 m horizontal well. It can be seen that the stiff controller can fast achieve desired rotary setting point, and there exists severe stick slip.
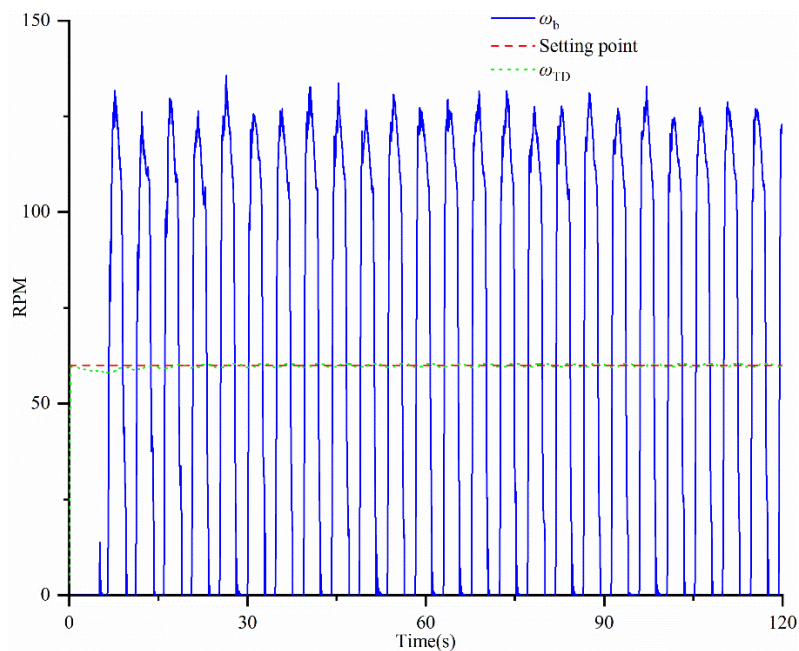

Figure 3. Step response of the 3600 m drill string system with a stiff PI controller

For the NMPC, the drill string system is reduced to have only 4 states. Figure 4 presents the performances of NMPC with two different control horizon hc, and the hp is set to 5.0 s. It shows the NMPC can effectively remove stick slip, but there still exist torsional vibrations, and a smaller hc (0.5 s) produces a better result. However, hc cannot be further reduced because of the limit of computational time, and a more reduced model than the current one having 4 states may damage the accuracy.

Figure 5 shows the ZTorque controller performance with a 50% matching, which means 50% of filtered torque is used in producing top drive torque output. Comparing the ZTorque performance with those of NMPC, the conclusion is that the NMPC with a 0.5s hc outperforms ZTorque controller.
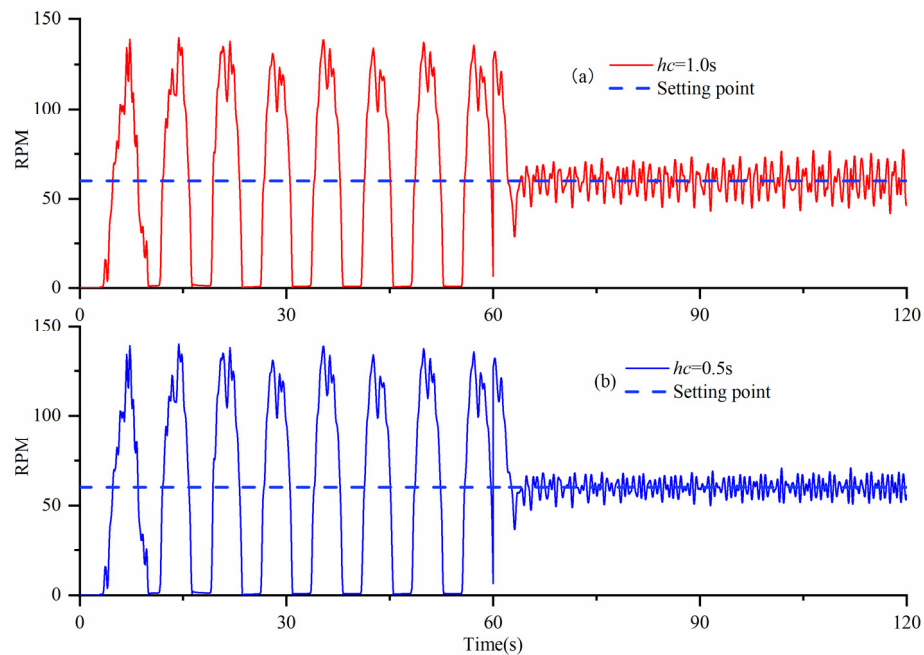
Figure 4. The performances of NMPC against the 3600 m drill string system with two different *hc*
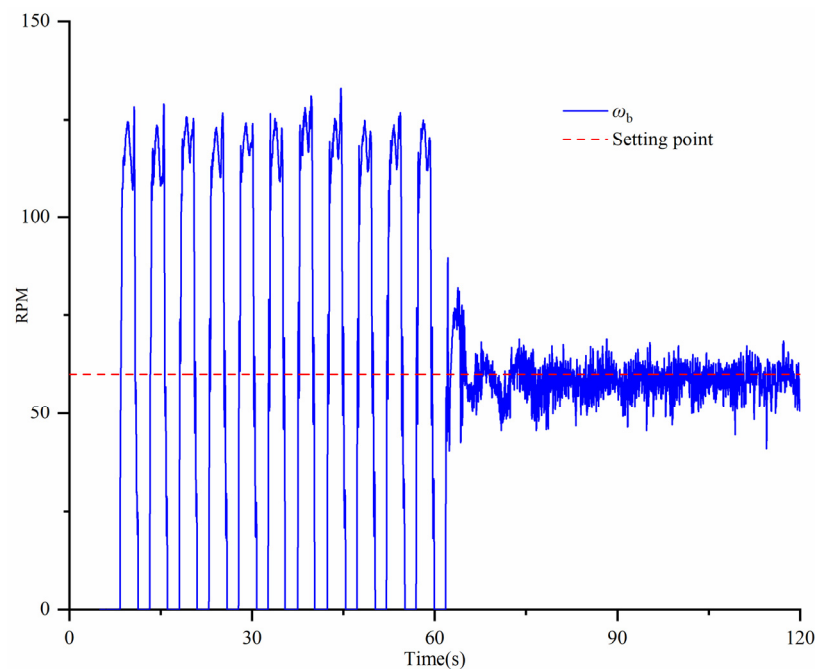

Figure 5. The performance of ZTorque against the 3600 m drill string system, 50% matching

For the 5500 m drill string system, the reduced NMPC model has 7 states, and control horizon *hc* is set to as 1.0 s. Figure 6 compares the performances of ZTorque and NMPC controllers. From which we can see that there is still torsional vibration with NMPC, and ZTorque outperforms NMPC. But the torsional vibration magnitude in NMPC case is not very severe, and is far better than no control. Compared to ZTorque, NMPC does not need such a high-frequency torque measurement, which can be seen as an advantage of NMPC.
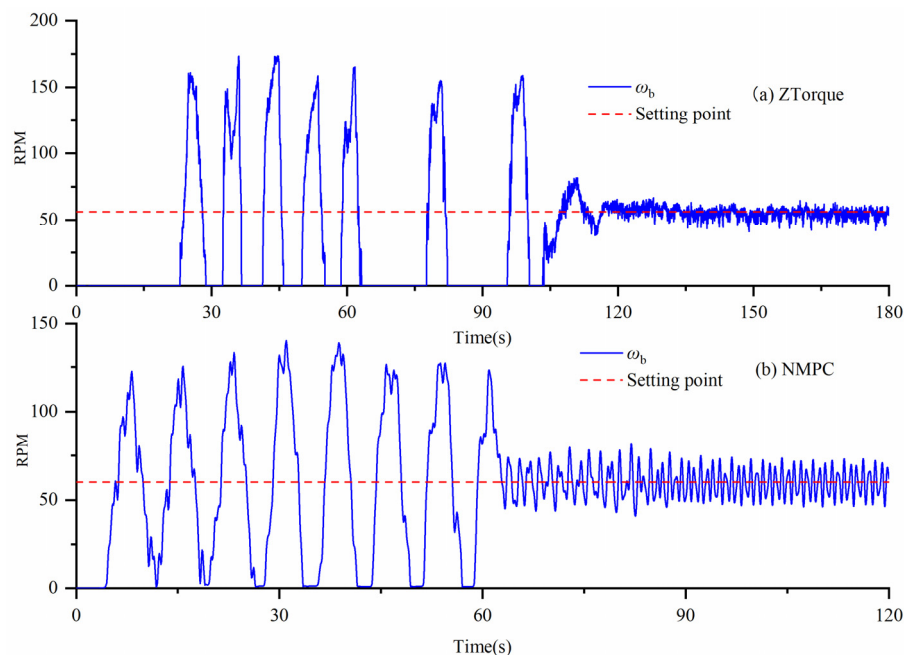
Figure 6. Performances of ZTorque 100% matching and NMPC against the 5500 m drill string system

4. Conclusions

This work explores the feasibility of using NMPC to mitigate stick slip in drilling. To make real-time control possible, two techniques are used, namely nonlinear model reduction using balancing of empirical Gramians and asNMPC.

The simulation results indicate that the proposed NMPC can effectively remove stick slip, but in some cases there still exist torsional vibrations. For a longer drill string, NMPC performance is inferior than ZTorque, but it is far better than no control. One advantage of NMPC compared to ZTorque is that it does not need high-frequency torque measurement.

This is an ongoing research, future studies will focus on model reduction of nonlinear drill string system using other methods, like Sparse Identification.

References

[1]   Halsey, G. W., Kyllingstad, A., Kylling, A. (1988) Torque Feedback Used to Cure Slip-Stick Motion. In: SPE Annual Technical Conference and Exhibition, Houston.
[2]   Jansen, J. D. (1993) Nonlinear Dynamics of Oilwell Drillstrings. Delft University Press.
[3]   Dwars, S. (2015) Recent Advances in Soft Torque Rotary Systems. In: SPE/IADC Drilling Conference and Exhibition, London.
[4]   Pixton, D. S., Asgharzadeh Shishavan, R., Perez, H. D., Hedengren, J. D., Craig, A. (2014) Addressing UBO and MPD Challenges with Wired Drill Pipe Telemetry. In: SPE/IADC Managed Pressure Drilling & Underbalanced Operations Conference & Exhibition, Madrid.
[5]   Johannessen, M. K., Myrvold, T. (2010) Stick-Slip Prevention of Drill Strings Using Nonlinear Model Reduction and Nonlinear Model Predictive Control. Norwegian University of Science and Technology.
[6]   Zavala, V. M., Biegler, L. T. (2009) The advanced-step NMPC controller: Optimality, stability and robustness. Automatica, 45(1), 86-93.

[7]   Padoan, A., Forni, F., Sepulchre, R. (2020) Model reduction by balanced truncation of dominant
         Lure systems. arXiv preprint arXiv:2005.08241.