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ACTIVE CONTROL OF DRILL-STRING TORSIONAL DYNAMICS

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Abstract: This paper deals with the active vibration control of the drill-string torsional dynamics. The drill-spring is modelled as a two degree-of-freedom system: the rotations at the top and at the bit of the drill string. An external controlled torque is applied at the top of the drill-string. The nonlinear interaction between the rock and the bit is included in the model, and it is a function of the bit rotation, friction, rock properties and axial load. The control strategy employed is the PD-control strategy and the results are compared with the system with imposed speed at the top. The torsional stability for different weight-on-bit values and top speeds are analyzed. It is shown that the control strategy applied increases the stability region of the system, but more investigations are required.

Keywords: drill-string dynamics, nonlinear dynamics, torsional vibrations, active control, stick-slip

INTRODUCTION

Excessive vibration of drill-strings is a concern for the oil industry. The vibrations are responsible, for instance, for fatigue of the structure and harm of measurement equipment. This paper treats specifically torsional vibration control and stick-slip phenomenon, and there are many previous articles that dealt with this subject.

Concerning the nonlinear bit-rock interaction, Pavone and Desplans (1994) investigate the stick-slip phenomenon in drill-strings, and present measurements of the bit-rock interaction: bit rotational speed vs. torque on bit. It is derived a decaying exponential law for this relationship. In this paper, a regularized bit-rock interaction curve is employed (Khulief et al; 2007 and Sampaio et al; 2007).

Concerning control strategies, Serrarens et al (1998) consider a torsional vibration model, which is controlled with H-infinity control strategy. Viguié et al (2009) consider a torsional vibration model, which is controlled with a nonlinear passive targeted energy transfer. A lightweight is attached to the system and a nonlinear energy sink is created. Kreuzer and Steidl (2012) consider a torsional vibration model, which is controlled by exactly decomposing the drill string dynamics into two traveling waves traveling in the direction of the top drive and in the direction of the drill bit.

Al-Hiddabi et al (2002) consider a coupled torsional-lateral model, which is controlled with a non-linear dynamic inversion control. Christoforou and Yigit (2003) consider a coupled model for axial-lateral-torsional vibrations, which are controlled using feedback control. Tucker and Wang (2003) consider a coupled model for axial-lateral-torsional vibrations (Cosserat theory), and compare feedback control strategies. More recently, Besselink et al (2016) propose a feedback control strategy to mitigate torsional stick-slip oscillations using a coupled axial-torsional model for the drill-string. Hong et al (2016) consider a coupled torsional-lateral model, which is controlled with a linear quadratic Gaussian (LQG) control strategy.

This paper investigates a PD-control strategy for the control of the torsional vibrations of a drill-string, and the stability map (top speed vs. weight-on-bit) is explored. The first section of this paper depicts the 2DOF system considered in the analyses, as well as the control strategy proposed for the problem. The second section presents the numerical results and, finally, the concluding remarks are made in the last section.

FORMULATION

Dynamical Model

A 2DOF torsional system is considered, where the degrees-of-freedom are θ_0 and θ_{bit}, which are the rotations of the top drive and of the BHA/bit. Figure 1 shows a sketch of a drill-string. A control law is applied at the top drive and a nonlinear bit-rock interaction torque occurs at the bottom of the column.

The BHA is considered a rigid body, and the drill-pipe is flexible. The stiffness of the column is given by $k = GJ_p/L_p$, where G is the shear modulus, L_p is the length of the drill-pipe and $J_p = (\pi/4)(r_{po}^4 - r_{pi}^4)$, in which r_{pi} and r_{po} are the inner and outer radius of the drill-pipe. The equivalent moment of inertia of the column is given by $I = \rho(J_b L_b + 1/3 J_p L_p)$, where L_b is the length of the BHA and $J_b = (\pi/4)(r_{bo}^4 - r_{bi}^4)$, in which r_{bi} and r_{bo} are the inner and outer radius of the BHA. The top drive moment of inertia is I_0 and it is assumed a viscous damping with parameter c.

The equations of motion of the system are given by

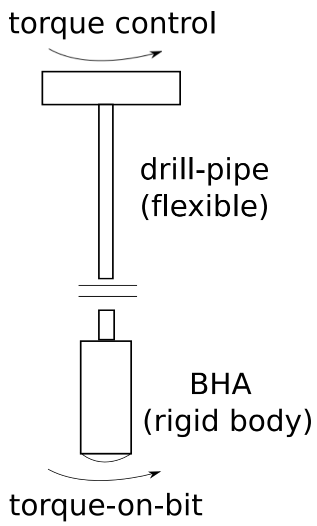

Figure 1 – Sketch of a drill-string.

$$
\begin{aligned}
I_0\ddot{\theta}_0 &= k(\theta_{bit}-\theta_0)+c(\dot{\theta}_{bit}-\dot{\theta}_0)+T_{top}\,,\\
I\ddot{\theta}_{bit} &= k(\theta_0-\theta_{bit})+c(\dot{\theta}_0-\dot{\theta}_{bit})+T_{bit}\,,
\end{aligned}
\tag{1}
$$

where the torque at the top and the torque at the bit (Khulief et al; 2007 and Sampaio et al; 20007) are

$$
\begin{aligned}
T_{top}(\theta_0) &= T_{control}(\theta_0)\,,\\
T_{bit}(\theta_{bit}) &= \mu\bar{r}WOB\left(\tanh(\alpha_3\dot{\theta}_{bit})+\frac{\alpha_1\dot{\theta}_{bit}}{1+\alpha_2\dot{\theta}_{bit}^2}\right)\,.
\end{aligned}
\tag{2}
$$

The parameters of the nonlinear bit-rock interaction model are μ, friction coefficient, $\bar{r}$, equivalent bit radius, WOB, axial force at bottom of the column, and α_1, α_2 and α_3, parameters that depend on the rock properties and cutting characteristics. Figure 2 shows the nonlinear bit-rock interaction for two different values of the weigh-on-bit (WOB).

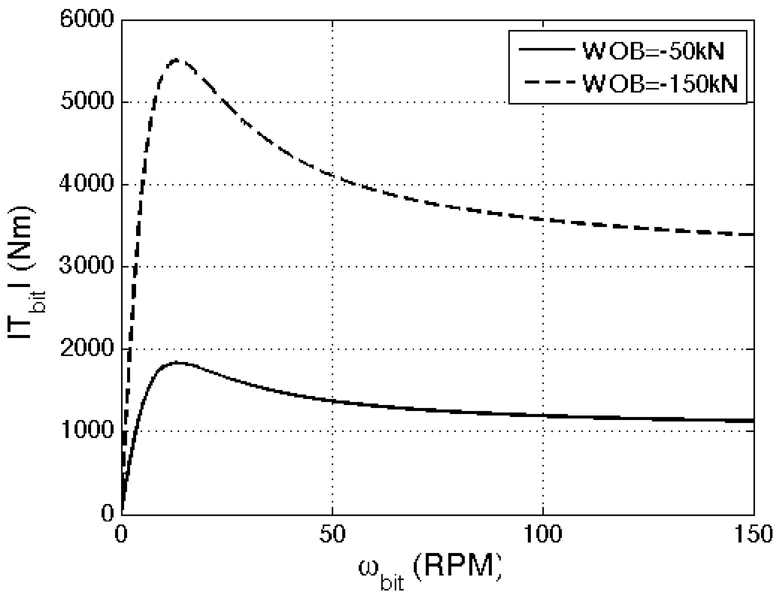

Figure 2 – Torque applied to the bit due to the bit-rock nonlinear interaction.

The state space model is given by:

$$
\dot{\mathbf{y}} = \begin{bmatrix} 0_{2\times2} & I_{2\times2} \\ -M^{-1}K & -M^{-1}C \end{bmatrix}\mathbf{y} + \begin{bmatrix} 0_{2\times1} \\ M^{-1}T(\mathbf{y}) \end{bmatrix}\,,
\tag{3}
$$

where $I_{2\times2}$ is the two by two identity matrix, $0_{2\times2}$ is the two by two zero matrix, $0_{2\times1}$ is the zero two dimensional vector, and

$$\mathbf{y}=\begin{bmatrix}\theta_o\\ \theta_{bit}\\ \dot{\theta}_o\\ \dot{\theta}_{bit}\end{bmatrix}\quad,\quad M=\begin{bmatrix}I_0 & 0\\ 0 & I\end{bmatrix}\quad,\quad C=\begin{bmatrix}c & -c\\ -c & c\end{bmatrix}\quad,\quad K=\begin{bmatrix}k & -k\\ -k & k\end{bmatrix},\quad T(\mathbf{y})=\begin{bmatrix}T_{top}(\theta_0)\\ T_{bit}(\theta_{bit})\end{bmatrix}. \tag{4}$$

Control strategy

A PD-control strategy that tries to maintain the rotation at the top drive at $\omega_{ref}t$ is considered, with ω_{ref} the constant speed. The control gain coefficients are k_P, proportional gain, and k_D, derivative gain.

$$T_{top}(\theta_0)=k_P(\omega_{ref}t-\theta_0)+k_D(\omega_{ref}-\dot{\theta}_0)\,. \tag{5}$$

This PD-control strategy will be compared with the results of the system with imposed speed at the top ω_{ref}. In this case, the drive torque assumes any value necessary to maintain the reference speed, and only one equation must be solved:

$$I\ddot{\theta}_{bit}=k(\omega_{ref}t-\theta_{bit})+c(\omega_{ref}-\dot{\theta}_{bit})+T_{bit}\,. \tag{6}$$

NUMERICAL RESULTS

The feedback control gain coefficients are constraint to $k_p\in[0,10^5]$ and $k_d\in[0,10^3]$. The following system parameters are used for the numerical example $G=70$ GPa, $\rho=7850$ kgm^3, $c=60$ Nsm, $D_o=0.150$ m, $d_o=0.120$ m, $D_i=d_i=0.095$ m, $L_p=2000$ m, $L_b=200$ m, $\alpha_1=2$ s^{-1}, $\alpha_2=1\ s^{-2}$, $\alpha_3=1\ s^{-1}$, $\mu=0.02$, which give:

$$M=\begin{bmatrix}03.09 & 0\\ 0 & 61.85\end{bmatrix}\quad,\quad C=\begin{bmatrix}60 & -60\\ -60 & 60\end{bmatrix}\quad,\quad K=\begin{bmatrix}240 & -240\\ -240 & 240\end{bmatrix}. \tag{7}$$

The torque at the bit is applied after 50s so that the transient is over. The Runge-Kutta integration sheme is applied to approximate the solution of the differential equations. The control gain coefficients are obtained performing an optimization problem, where the objective function to be minimized is $||\dot{\theta}_0-\omega_{ref}||$. That is, for each pair $\{\omega_{ref}^{(i)},WOB^{(i)}\}$, an optimization problem is solved to compute the optimal gain coefficients $\{k_p^{(i)},k_d^{(i)}\}$. Optimization has been carried out using *fmincon* (interior-point algorithm) in Matlab with zeros as lower limit and $[1\times10^5$ and $1\times10^3]$ as upper limit for the gains. The optimisation calls the *ode45* function and solves the response at every feedback gain in order to minimise the cost function.

In addition, we consider the stick-slip severity factor defined by $SSS=(\omega_{max}-\omega_{min})/(2\omega_{ref})$. This is how we interpret this factor. If the bit speed reaches a constant speed, which is equal to the reference speed at the top, this factor equals to zero and the system is stable. If there is a limit cycle oscillation for the bit speed, this factor is greater than zero, and the system is considered unstable.

Figure 3(a) shows the response for an imposed speed of 114.3 RPM and $WOB=-114.3$ kN, and Fig. 3(b) shows the response using the PD-control strategy with identified control gain coefficients of $k_p=818$ and $k_d=1000$. As explained before, the bit-rock nonlinear interaction model is turned on only after 50 seconds.

After 50 seconds it can be noticed that the bit speed presents a severe torsional oscillation when the speed is imposed at the top, and this dynamics is considered unstable. However the bit speed ends up with a constant value when the PD-control strategy is applied (stable behavior). Therefore, for this combination of values of RPM and WOB the extra degree of freedom at the top together with the control strategy benefit the stability of the system. This is not always the case.

Figure 4(a) shows the response for an imposed speed of 50 RPM and $WOB=-114.3$ kN, and Fig. 4(b) shows the response using the PD-control strategy with identified control gain coefficients of $k_p=19$ and $k_d=8$. One can see that the oscillations are less severe when the speed is imposed at the top ($SSS=1.4$), than when applying the PD-control strategy ($SSS=4.8$). A more detailed analysis should be done concerning the optimization problem to obtain the control gain coefficients. It is likely that the presented results might be improved if the optimization problem is improved.

To summary the numerical results, Fig. 5(a) shows the stability map obtained when applying the PD-control strategy and Fig. 5(b) shows the stability map obtained by the model that imposes the speed at the top. An 8×8 grid is considered and the contour plot represents the values of the stick-slip severity factor.

Some remarks should be made. First, it can be noticed that the maximum values for the stick-slip severity factor SSS is much higher when applying the PD-control strategy, Fig. 5(a). Sometimes we are not able to find good control gain coefficients and the torsional oscillation of the response becomes important. Second, it is obverved that the stable region (dark blue) is increased when applying the PD-control strategy. That is, somehow the extra degree of freedom (top speed)

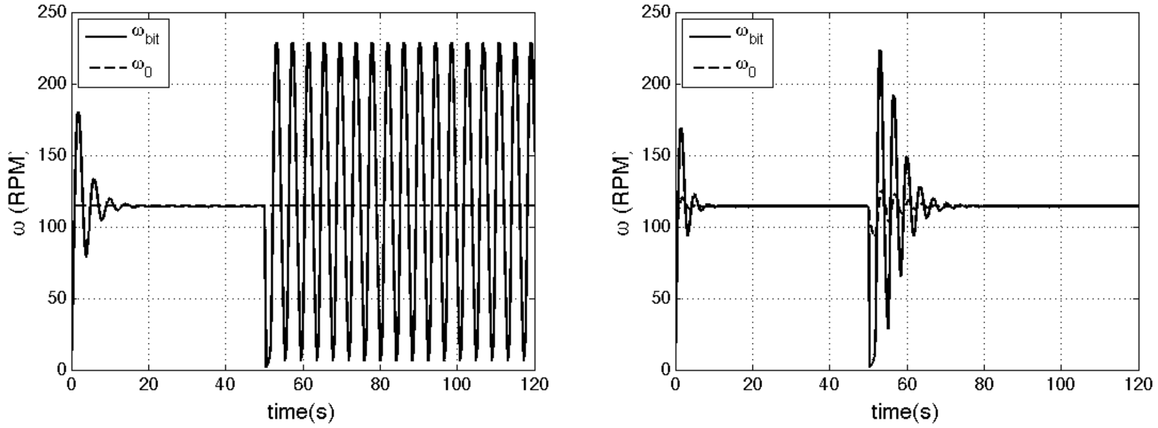

Figure 3 – Speed at the top (dashed line) and of the bit (continuous line) for (a) imposed speed at the top and (b) PD-control strategy. Point (114.3 RPM, -114.3 kN WOB).

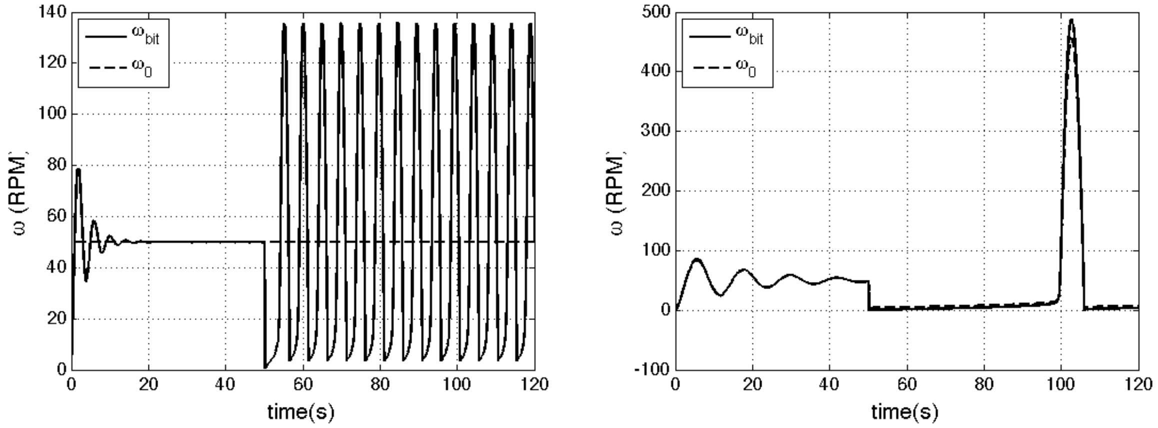

Figure 4 – Speed at the top (dashed line) and of the bit (continuous line) for (a) imposed speed at the top and (b) PD-control strategy. Point (50 RPM, -114.3 kN WOB).

controlled by this strategy benefits the stability of the system. Finally, the figure shows that there is a region at the right bottom that presents a worst dynamics comparing the PD-control strategy with the imposed speed at the top. Thus, the optimization problem to obtain the control gain coefficients should be improved, and also other control strategies should be pursued.

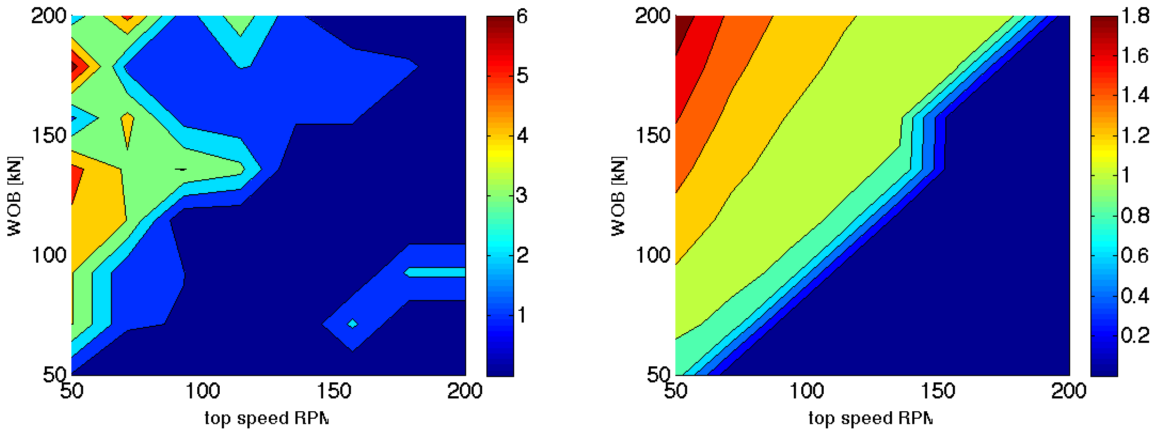

Figure 5 – Stability map (a) PD-control strategy and (b) imposed speed at the top. The colors represent the values of the stick-slip severity factor.

CONCLUDING REMARKS

This paper considers the PD-control strategy for the active vibration control of the drill-string torsional dynamics. The drill-string is modelled as a two degree-of-freedom system: rotations at the top and at the bit of the drill string. The nonlinear interaction between the rock and the bit is also included in the model, which is a function of the angular velocity, friction, rock properties and axial load. A stability map is constructed to assess the torsional stability of the system for different reference speeds at the top and different values of the weight-on-bit. The stability map obtained with the PD-control strategy is compared with the one obtained with a speed imposed at the top. It was shown that the PD-control strategy was able to increase the total region of stability of the system, but it yielded worst results for some specific regions. The optimization problem considered to obtain the control gain conefficients should be improved, and other control strategies must be persued.

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