

# Design of a Controller for Suppressing the Stick-slip Oscillations in Oil well Drillstring

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## Abstract

*In oil well drilling operations, one of the important problems to deal with is represented by the necessity of suppressing harmful stick-slip self-excited oscillations. This oscillation is a source of failures which reduce rate of penetration (ROP) and increase drilling operation costs. Stick-slip leads to excessive bit wear, premature tool failures and a poor rate of penetration. In this paper we propose to use the weight on the bit ( $W_{OB}$ ) force as an additional control variable to compensate stick-slip oscillations. We use changes of torque applied to drillstring for adaptation of  $W_{OB}$ . Torque and  $W_{OB}$  are both measurable and bit speed and bit torque is not necessary. Simulations applying this method show that the stick-slip oscillations can be eliminated without requiring a re-design of the velocity rotary-table control.*

**Keywords:** Oil well drilling, weight on bit ( $W_{OB}$ ), stick-slip, Dynamic model.

## Introduction

There has for the past 50 years been conducted extensive research on the subject of torsional vibrations on drill strings used by the oil industry<sup>1</sup>. These torsional vibrations are an important cause for deteriorated drill string performance. They can lead to premature failure of bits, motors and other expensive components used in drilling operations. One of the main reasons for torsional vibrations is the stick-slip phenomenon<sup>2</sup>. The phenomenon is characterized by stick-phases, where the rotation comes to a complete stop, and slip-phases where the angular velocity of the bit increase up to three times its nominal value<sup>3</sup>. This undesirable motion of the bit will not only lead to unwanted wear, but also significantly reduce the rate of penetration (ROP), which is an important consideration financially associated with drilling operations. Many ways of reducing these vibrations have been proposed, both from practical and theoretical viewpoints. Historically, the experience of drillers has revealed that the manipulation of different drilling parameters (increasing the rotary speed, decreasing the weight-on-bit ( $W_{OB}$ ), modifying the drilling mud characteristics, introducing an additional friction at the bit<sup>4</sup>, etc). However, this strategy depends too much on the personal skills of each drilling technician to be really effective.

More effective control methodologies have appeared in the literature in order to compensate drillstring stick-slip vibrations. In 1998, a  $H_\infty$ -control method to suppress stick-slip oscillations on a contemplated system has been proposed<sup>2</sup>.  $H_\infty$ -control has been a widely used solution in controlling vibration problems, such as in cutting processes where it is used to suppress machine tool chatter. Another method to suppress stick-slip oscillations is to use the weight on bit as an additional control variable. This method, called Drilling Oscillation KILLer (D-

OSKIL), was introduced in<sup>4,5</sup>. In this method when the stick-slip oscillations occur, the drillstring pulled upward to reduce WOB. In<sup>3</sup> bit-velocity varying WOB is introduced.

## Dynamic Modeling of a Drillstring

Drillstring systems are used by the oil industry to extract gas and oil from earth surface. With rotating the bit connected to end of drillstring, by rotary table or top drive a hole is made on the surface of the earth crushing the rock formation<sup>1</sup>. The drillstring consists of the BHA and drill pipes screwed end to end to each other to form a long pipe. The BHA comprises the cutting device, regarded as bit, stabilizers (at least two spaced apart) which prevent the drillstring from underbalancing, and a series of pipe sections which are relatively heavy known as drill collars. Drillstrings usually include at the top of the BHA a section of heavy-weight drill pipe. While the length of the BHA remains constant, the total length of the drill pipes increases as the borehole depth does so and can reach several kilometers<sup>3</sup>.

Multiple kind of models have been used in literature to describe drillstring systems. However, lumped parameters models have been shown to be valid enough to properly describe the stick-slip oscillation phenomena and easy enough to make the study not too complex<sup>3-7</sup>.

The model used here (figure 2) is a two-degree-of-freedom model with two inertial masses  $J_r$  and  $J_b$ , locally damped by  $c_r$  and  $c_b$ . The inertias are coupled with each other by an elastic shaft of stiffness  $k$  and damping  $c$ . The variables  $\varphi_r$  and  $\varphi_b$  stand for the rotary and the bit angle. The rotary torque control signal  $T_m$  used to regulate the rotary angular velocity  $\dot{\varphi}_b$ . The  $T_b$  represents the total friction ( $T_{fb}$ ) and viscosity torque over the drill bit.

The model equations are the following:

$$J_r \ddot{\varphi}_r + c(\dot{\varphi}_r - \dot{\varphi}_b) + k(\varphi_r - \varphi_b) = T_m - T_r(\dot{\varphi}_b) \quad (1)$$

$$J_b \ddot{\varphi}_b - c(\dot{\varphi}_r - \dot{\varphi}_b) - k(\varphi_r - \varphi_b) = -T_b(\dot{\varphi}_b) \quad (2)$$

and,

$$T_r(\dot{\varphi}_r) = c_r \dot{\varphi}_r + T_{c_r} \operatorname{sgn}(\dot{\varphi}_r) \quad (3)$$

$$T_b(\dot{\varphi}_b) = c_b \dot{\varphi}_b + T_{f_b}(\dot{\varphi}_b) \quad (4)$$

And we use the equations (5), (6) and (7) to describe the friction torque over the drill bit.

$$T_{f_b}(x) = \begin{cases} T_{e_b}(x) & \text{if } |\dot{\varphi}_b| < D_v, \quad |T_{e_b}| \leq T_{s_b} \\ T_{s_b} \operatorname{sgn}(T_{e_b}(\dot{\varphi}_b)) & \text{if } |\dot{\varphi}_b| < D_v, \quad |T_{e_b}| > T_{s_b} \\ R_b W_{ob} \mu_b(\dot{\varphi}_b) \operatorname{sgn}(\dot{\varphi}_b) & \text{if } |\dot{\varphi}_b| > D_v, \end{cases} \quad (5)$$

$$\mu_b(\dot{\varphi}_b) = [\mu_{c_b} + (\mu_{s_b} - \mu_{c_b}) e^{-\gamma_b |\dot{\varphi}_b|}] \quad (6)$$

$$T_{e_b}(x) = c(\dot{\varphi}_r - \dot{\varphi}_b) + k(\varphi_r - \varphi_b) - c_b \dot{\varphi}_b \quad (7)$$

Where  $x = (\varphi_r, \dot{\varphi}_r, \varphi_b, \dot{\varphi}_b)^T$  is the system state vector,  $\mu_b(\dot{\varphi}_b)$  is the velocity-depending dry friction coefficient at the bit,  $\mu_{s_b}$ ,  $\mu_{c_b}$  are the static and Coulomb friction coefficients associated with the inertia  $J_b$  with  $0 < \mu_{c_b} < \mu_{s_b} < 1$ ,  $\gamma_b$  is a positive constant,  $T_{s_b}$  is the static friction torque associated with  $J_b$  and  $T_{s_b} = R_b W_{ob} \mu_{s_b}$ ,  $R_b$  is the bit radius,  $W_{ob}$  is the WOB, which is directly related with the hook-on-load applied at the surface,  $T_{e_b}(x)$  is the applied external torque that must overcome the static friction torque  $T_{s_b}$  to make the bit move, and  $D_v > 0$  specifies a small enough neighborhood of  $\dot{\varphi}_b = 0$ . The resulting friction model is represented in Figure 2, and it is compared with a classical dry friction model with an exponential-decaying law at the sliding phase. The dry friction torque  $T_{f_b}$  for  $\dot{\varphi}_b > 0$  varies between  $T_{s_b}$  and  $T_{c_b} = R_b W_{ob} \mu_{c_b}$ .

Assuming  $T_m = u$  as control input, a PID control action is added to the model at the top end of the drillstring in order to maintain the top velocity constant<sup>1</sup>. Then:

$$u(t) = K_p(\bar{\Omega}t - \varphi_r) + K_d(\bar{\Omega} - \dot{\varphi}_r) + K_i y \quad (8)$$

With  $\bar{\Omega}$  the reference velocity,  $y = \int_{t_0}^t (\bar{\Omega} \tau - \varphi_r(\tau)) d\tau$ ,

and  $K_p > 0$ ,  $K_d > 0$ ,  $K_i > 0$  and  $t_0 > 0$ . Control  $u$  is saturated to some value  $u_{max} > 0$ ,

$$|u| \leq u_{max}$$

According to field experience, the increase of  $\Omega$  and the decrease of the  $W_{ob}$  can make stick-slip disappear<sup>3</sup>.

The model parameters used for the simulations are extracted from<sup>3</sup>:  $J_r = .518 \text{ kgm}^2$ ,  $J_b = 0.0318 \text{ kgm}^2$ ,  $c_r = 0.18 \text{ Nms/rad}$ ,

$c = 0.0001 \text{ Nms/rad}$ ,  $c_b = 0.03 \text{ Nms/rad}$ ,  $k = 0.073 \text{ Nm/rad}$ ,  $T_{c_b} = 5 \text{ Nm}$ ,  $T_{s_b} = 8 \text{ Nm}$ ,  $T_{c_r} = 0.5 \text{ Nm}$ ,  $D_v = 10^{-6}$ ,  $\gamma_b = 0.9$ ,  $u_{max} = 20$ ,  $K_p = 3$ ,  $K_d = 10$ ,  $K_i = 4$ .

Figure 4 presents the block diagram of drilling system and closed loop speed control. In figure 1 and figure 5, a comparison between stick-slip oscillations measured in the field (Figure obtained from<sup>4</sup>) and the ones produced by simulating the closed-loop system in Matlab/Simulink can be seen. Inertias, stiffness and damping coefficients correspond to a reduced-scale model extracted from<sup>3</sup>. Although these values do not correspond with real parameters, they can be used to describe the behavior of the drillstring.

## Designing the Stick-Slip Compensator

From simulation studies and figure 5 we can say that approximately when bit sticking the torque on surface ( $T_m$ ) is decreasing and when bit slipping torque is increasing. If we increase the  $W_{ob}$  when slipping, the maximum speed of bit is reduced and duration of slipping will be longer. And if we decrease the  $W_{ob}$  when bit sticking the duration of sticking is reduced.

It is concluded that the manipulation of the  $W_{ob}$  can be a solution for stick-slip oscillations. The variation of the  $W_{ob}$  is proposed as follows:

$$W_{ob} = W_{ob0} - \alpha \frac{\partial}{\partial t} T_m \quad (9)$$

for avoiding from unwanted conditions and lowering the ROP,  $W_{ob}$  must be saturated to maximum %20 of nominal  $W_{ob}$  greater than  $W_{ob0}$  and %20 of nominal  $W_{ob}$  lower than  $W_{ob0}$ .

$W_{ob}$ -variation low (9) can be applied to model.

## Simulation Results

Block diagram of drilling system with compensator is presented in figure 6 and result of simulation is presented in figure 7. In this simulation the compensator is turned on at  $t = 55$ s. In this case, although stick-slip cycles are suppressed. Oscillating behavior of bit speed may not desirable after turning on the compensator. The compensator makes little change in  $W_{ob}$  to eliminate the oscillation. After compensation,  $W_{ob}$  force recovers its nominal drilling value.

## Conclusion

A model describing the torsional behavior of a generic vertical oilwell drillstring has been presented and a model by manipulating  $W_{ob}$  for suppressing stick-slip oscillations has been proposed. Then make some simulations in Matlab\Simulink with applying the compensator. The control strategy achieves two main goals: i. the velocity at the top end of the drillstring is maintained to a reference value, ii. the bit velocity tracks the surface velocity with a reduction of the BHA sticking.

Drillstrings modeling oriented to the description of mechanical vibrations and the control of them are open research problems. In order to have more realistic models, the consideration of drillstring length, lateral and axial dynamics and the influence of

circulating drilling muds are needed. It is also necessary to make an analysis of the influence of the drillstring length, formation properties and bit characteristics in model parameters which would lead to a robust performance analysis.

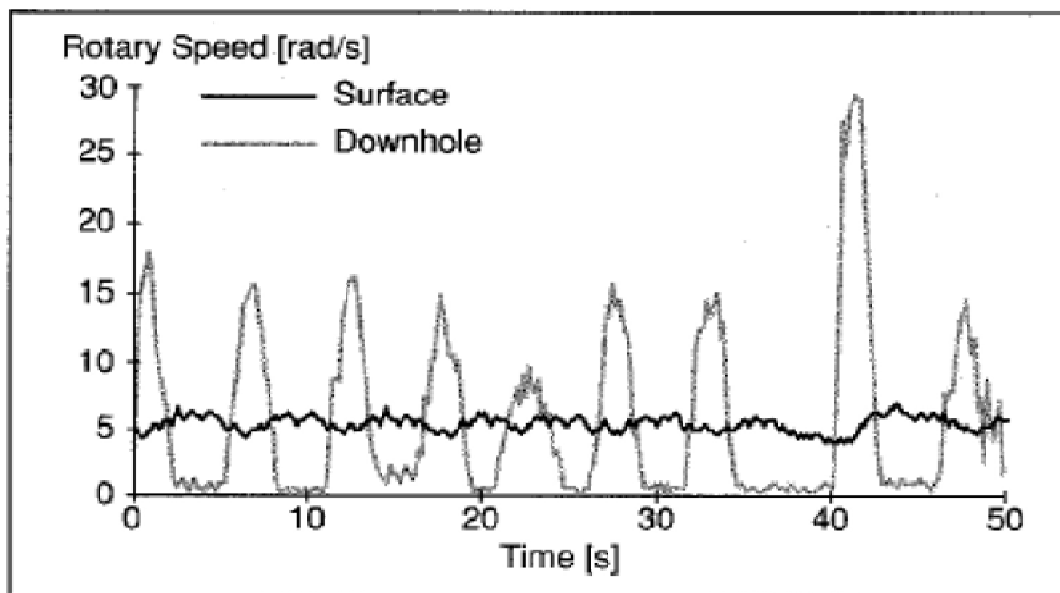


Figure-1  
Stick- slip oscillations measured in the field (Figure obtained from<sup>4</sup>)

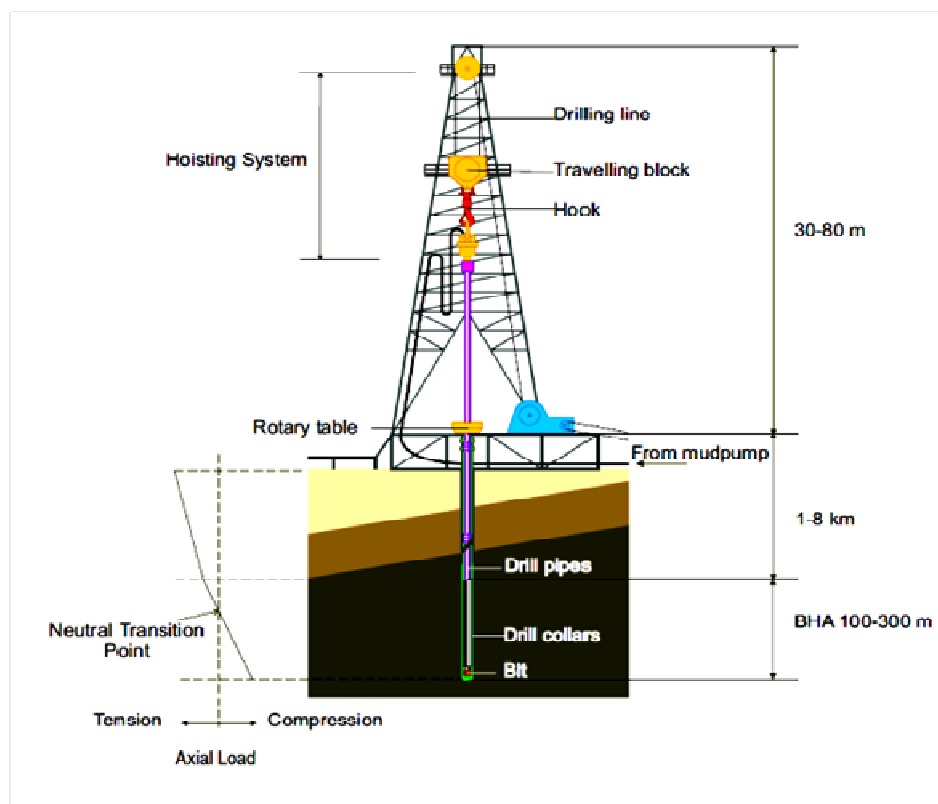
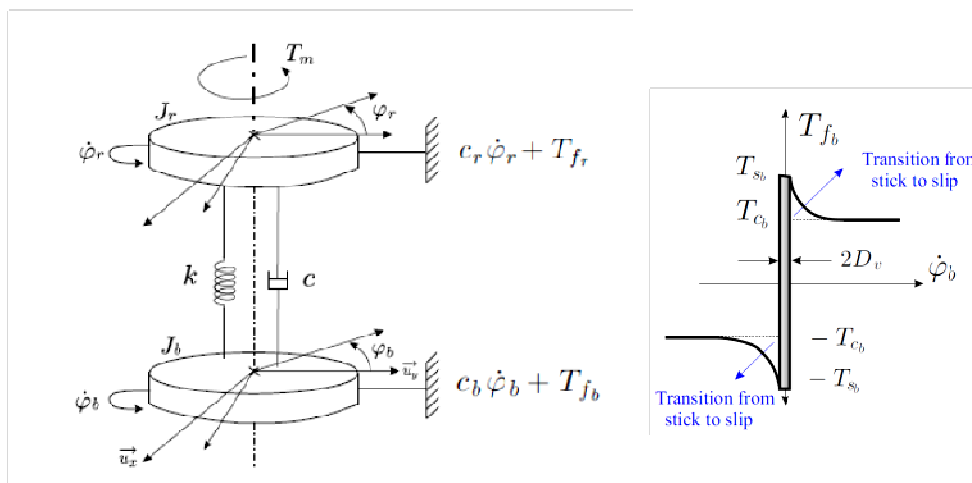
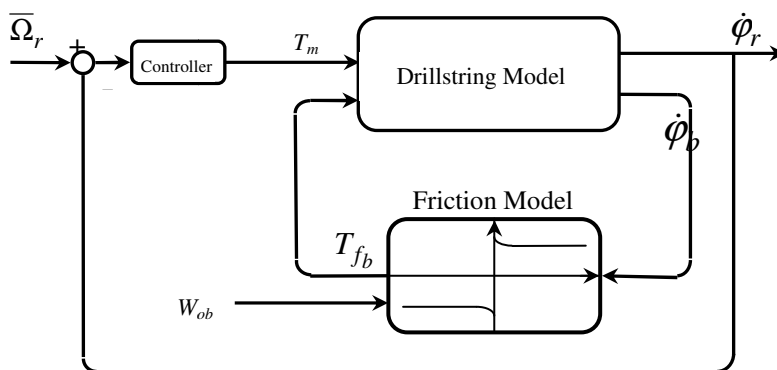


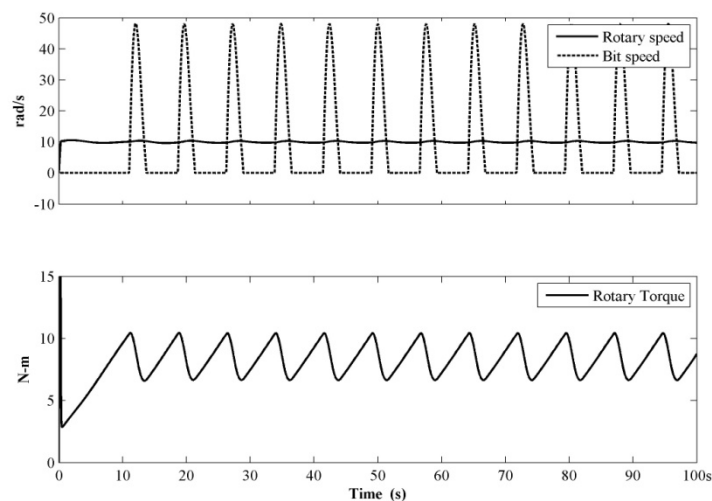
Figure-2  
Drilling Equipment



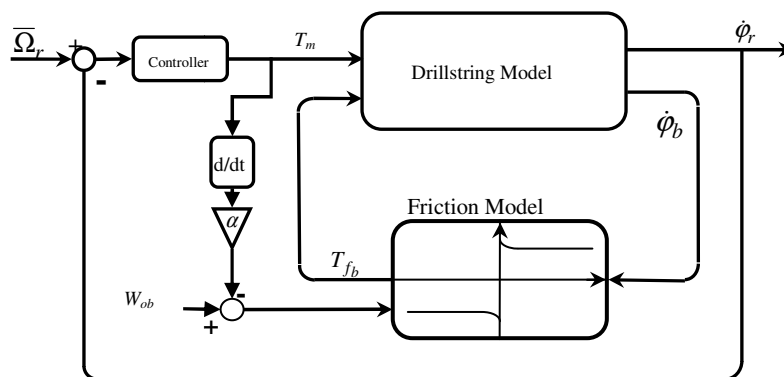
**Figure-3**  
Mechanical model of drillstring and friction model



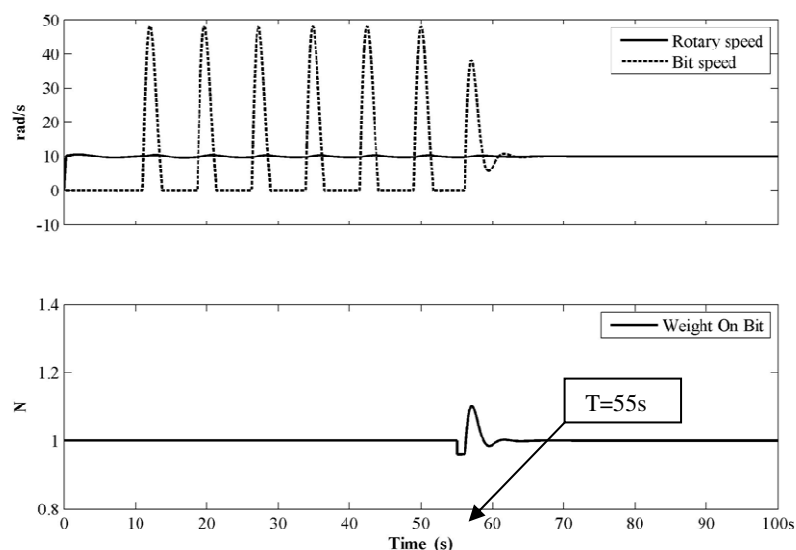
**Figure-4**  
Block diagram of drilling system



**Figure-5**  
Stick-slip oscillation in Bit speed produced by simulating the closed-loop system in Matlab/Simulink (Simulation with  $\Omega = 10 \text{ rad/s}$  and  $W_{ob}=1N$ )



**Figure-6**  
**Block diagram of drilling system with compensator**



**Figure-7**  
**Simulation results of system with compensator (turned on at t=55s)**

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