Estimation of downhole and bit-rock interaction parameters in real-time using an adaptive observer for drilling processes

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Summary. Understanding the happenings at the downhole is extremely important for developing a fully automated drilling system. Towards achieving the same, in this work, an adaptive model-based observer is developed for the real-time estimation of the downhole parameters along with the bit-rock interaction parameters. The bit-rock interaction parameters in real-time will help us in understanding any formation changes along with the occurrence of other unwanted dynamics at the bit-rock interface. In this work, the off-bottom field dynamics model is combined with the bit-rock interaction law and is validated against the field data for wells drilled in North America. The results obtained were satisfactory and highlight the adaptive nature of the soft sensor.

Abstract

Obtaining real-time estimates of the bit-rock interaction (BRI) parameters and real-time formation pose significant challenges in developing an automated closed-loop geo-steering system for drilling operations. A major challenge for the same is the prohibitively expensive high bitrate and low latency downhole telemetry systems. Drilling dynamics can be broadly divided into off-bottom and on-bottom dynamics. Recent results have successfully captured the significant dynamics for off-bottom dynamics and have been validated against the field data [1]. However, developing an on-bottom dynamics field validated model is faced with significant challenges in accurately estimating the bit-rock interaction parameters, which in turn aid in estimating formation detection in real-time. A simulation-validated on-bottom dynamics model was recently proposed by Auriol et al. [2]. The model was developed based on the understanding of bit-rock interaction as proposed by Detournay and Defourny [3]. The BRI law, proposed by Detournay and Defourny, is dependent on friction coefficient at the rock contact, bit constant, depth of cut, intrinsic specific energy of the rock, drilling strength, and weight-on-bit (WOB). Auriol et al. [2] modified the BRI law by simplifying the model whose BRI parameters are dependent on WOB and depth of cut. The variations in the BRI parameters give insights into the happenings of drilling at the interface of the drillstring. Any formation change is reflected in the form of changes in these parameters that give a clear understanding of the drilling environment.

The off-bottom dynamics field validated model is based on the distributed drillstring model and uses only the surface parameters, RPM, and torque. In the proposed on-bottom dynamics model, the modified BRI law proposed by Auriol et al. is combined with the field-validated off-bottom dynamics model. Coupled with the surface RPM and surface torque, the proposed model uses additional surface measurements, weight-on-bit, differential pressure, flow rate to estimate the downhole RPM, downhole torque, and the BRI parameters. The proposed model assumes the torsional motion of the drill string to be the dominating dynamics behavior, a constant rate-of-penetration (ROP) and therefore a steady axial velocity of the bit, no distributed axial dynamics, and the friction coefficients along the drillstring are known. The proposed model is field validated against the field data obtained for an unconventional well drilled in North America.

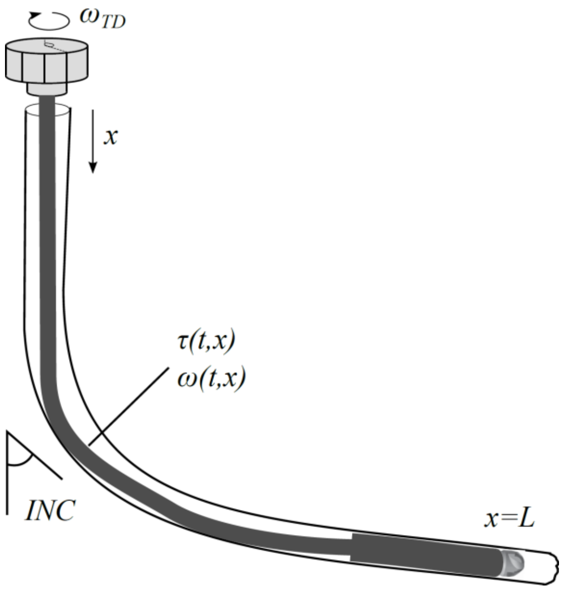

Figure 1: Schematic indicating the distributed drill string of length L lying in deviated borehole

For brevity, the mathematical model used in this work is described here. The distributed model used in this work is based on the works of Aarsnes and van de Wouw [4], however, only torsional dynamics have been considered. Figure 1 shows the angular velocity ($\omega(t,x)$) and torque ($\tau(t,x)$) with time ($0 < t < T$) and length ($0 \leq x \leq L$), representing the angular motion of the drillstring of length L for a time T and torque obtained using the shear strain that is given as twist per unit length. With J and G as the polar moment of inertia and shear modulus, ($\tau(t,x)$) as torque, and φ as the angular displacement in the string, the angular motion of the drillstring is given by $\frac{\partial\tau(t,x)}{\partial t} + JG\frac{\partial\omega(t,x)}{\partial x} = 0, J\rho\frac{\partial\omega(t,x)}{\partial t} + JG\frac{\partial\tau(t,x)}{\partial x} = S(t,x)$, with ρ being the density.

$S(t,x)$ is the source term due to frictional contact with the borehole and is modeled as $S(t,x) = -k_t \rho J \omega(t,x) - F(\omega,t,x)$, with $F(\omega,t,x)$ being the differential inclusion that represents the Coulomb friction between the drillstring and the borehole. This off-bottom dynamics model cannot estimate the bit torque. To calculate the bit-torque, the BRI law as given by Detournay and Defourny [3] is included to the off-bottom dynamics as $\tau_b = a_1 * WOB + a_2 * \frac{ROP}{RPM}$. The on-bottom dynamics model is essentially developed by the inclusion of the BRI law to the off-bottom dynamics model.

The soft sensor developed in this work is the extension of the same developed for the off-bottom dynamics field validated model that provides estimates for downhole torque and the BRI parameters along with the downhole RPM by using only the surface measurements. The model is initiated with the off-bottom dynamics and initially estimates the friction coefficients (static and kinetic), and the BRI is not activated. With initial guess values for the friction coefficients, the model is initiated and the same are obtained till the bit is fully engaged with the bottom, where the model switches from off-bottom dynamics to on-bottom dynamics. Before the model switches to on-bottom, the convergence criterion is enforced for the friction coefficients. For each depth, the values of friction coefficients are different and those values around which the friction coefficients remain stable for a minimum of 20 seconds are considered as the converged values. Once the bit tags the bottom with the onset of the axial motion, the estimation of the friction coefficients is stopped and the BRI parameters along with the downhole torque are estimated. The main reason behind adopting such an approach is that the observer used in the model cannot distinguish between friction coefficients and the bit-rock interaction parameters. By using such an approach, the friction coefficients and the BRI parameters are estimated separately, without the need for any further complex mathematical model.

Figure 2 shows the normalized well profile of one of the wells for which the field data was used to validate the bit-rock interaction law implemented in the work along with the soft sensor. Figure 3 shows the profiles of the real and estimate of the surface torque along with the estimate for the downhole torque. The bit tags the bottom at 70 seconds and is fully engaged with the bottom at about 120 seconds, When the bit tags the bottom, the downhole torque is a combination of the surface torque and the motor torque. The downhole torque presented in figure 3 is the difference between the total torque available at the bit and the mud motor torque. The downhole torque shown in figure 3 is essentially the difference in the surface torque with the bit off-bottom and on-bottom. It should be noted here that the difference between the off-bottom and on-bottom surface torque is very small, and the model has been able to capture the same.

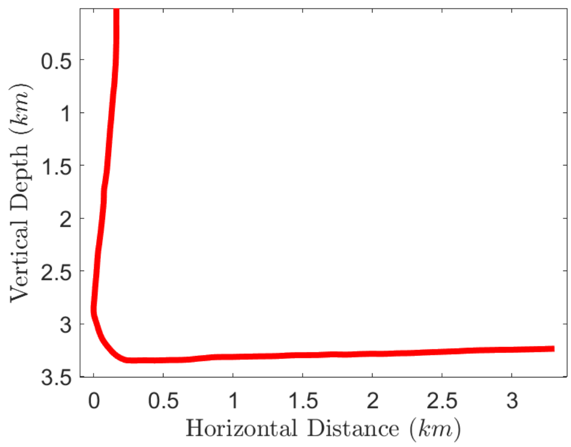

Figure 2: Normalized well profile

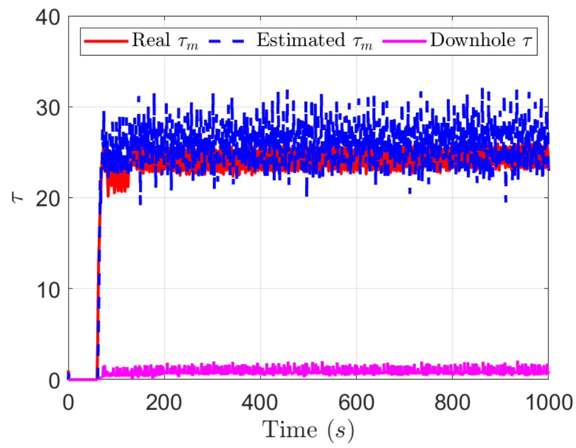

Figure 3: Surface and downhole torques profiles

The estimates provided by the proposed soft sensor were found to be robust to poor initial estimates. The vital feature of the observer is its ability of adaptive estimation. Convergence of the friction parameters is aided by the adaptive estimation nature of the soft sensor, which otherwise is computationally expensive using other techniques that include the industry-standard friction tests where the pipe is raised and then lowered. The model used in this work is computationally efficient, which is a result of its simplistic nature. This makes the proposed model an appealing candidate for online, real-time sensing systems for drilling applications.

References

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