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Automatic detection of abnormal torque while reaming

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ABSTRACT

A lumped element model is implemented to describe the torsional vibrations of the drillstring while reaming, i.e. rotating off-bottom. The rotary motions and the torques anywhere in the drillstring are simply convolutions of the surface rotary motion with analytical expressions that are derived in this paper. The Coulomb friction forces are divided into steady-state forces and time-dependent forces. The drillstring vibrates around a stable position that is determined by the steady-state friction torques. The vibrations are damped by viscous friction forces and in particular the Basset forces dominate the damping. The time-dependent part of the Coulomb friction forces are related to when something is not normal in the well. For instance, when the drill bit is hindered by a cuttings bed or the bottom part of the drillstring is hung up in a sharp curvature.

The model is further used in an algorithm for detecting the time-dependent Coulomb friction coefficients. A sensitivity study is added and the detection algorithm seems to be mathematically robust. This motivates experimental verifications of both the model and the detection algorithm in the future.

1. Introduction

When drilling and reaming deviated oil-wells, the drillstring is subjected to friction forces as it is scraping along the borehole wall. Monitoring these friction forces is a vital part of a normal drilling operation. After drilling each stand, which are typically 30 m, *up-weights* and *down-weights* are typically measured. The up-weight is the weight of the drillstring when pulling out with constant speed. The down-weight is the weight of the drillstring when running into the hole again with constant speed. The difference between the up-weight and the down-weight is an estimate of two times the sum of the friction forces in the wellbore. Typically, these graphs are plotted as functions of depth to give an overview of the friction in the well.

Another test that is frequently used is the measure of the *off-bottom torque*. The off-bottom torque is the torque of a rotating drillstring that is off-bottom and not moving axially. When this is done for each stand, a curve of torque as a function of depth is defined. In practice, these plots are used to diagnose the state of the well. The plots can reveal whether the hole is properly clean, in gauge or if there are any sharp curvatures.

Furthermore, when running drillpipe in or out of the hole, sharp changes in drillpipe weight can be encountered. The depths of such events are carefully noted and this information is used for diagnozing the operation. The drill bit and the stabilizers have reamers that enables the operator to remove these restrictions. However, excessive reaming increases the hole diameter locally, which can cause other problems such as vibrations, poor hole cleaning and difficulties with running casings into the hole.

The algorithm that is outlined in this paper can potentially be used to diagnose how much reaming is sufficient to clean a restriction without damaging the hole excessively. Moreover, since the detection algorithm can be enabled at all times, it can determine when the increased friction happens.

In addition to outlining the detection algorithm, the semi-analytical models in this paper provides a physical understanding of the impact of the influential friction forces in the well. The models are similar to the semi-analytical lumped element models that are described in Hovda (2018a,b), which are shown to generalize the models in Hovda (2017), Bavinck et al. (1994), Bavinck and Dieterman (1996) and Dieterman et al. (1995). The models coincide precisely when the viscosity is set to zero, the drillstring has a uniform diameter and the added mass effect is omitted.

In Hovda (2018a), the axial vibrations in a vertical drillstring is described, when rotation can be either on or off. Here, it is concluded that the viscous Basset forces dominate the damping term and that the effect of the added mass has a major effect on the pressure downhole.

In Hovda (2018b), the axial vibrations in a rotating drillstring in a deviated wellbore is described. It is proven that the Coulomb friction forces dominate the damping term and it is suggested that the Basset forces can be neglected. The axial motion is typically overdamped, unless the hole is only slightly deviated and/or the rotation speed is very high. A

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model that describes when the hole is deviated and the no rotation is present is given in Zhao et al. (2016). Here, it is reported that the axial stick-slip effect can cause large surge and swab pressures downhole.

It is suggested in Hovda (2018b) and furthermore argued for in this paper, that the axial and the torsional motions are decoupled when the rotation is on and the drill bit is off-bottom. However, in the case of drilling, these forces are severely coupled as outlined in for instance (Arvani et al., 2015). Modeling drilling is outside the scope of this paper, but such a model could potentially be benchmarked against the semi-analytical model that is presented in this paper.

It is also important to note that the modern technological evolution is moving in the direction of automation. Fully automatic drill floors are already in place and high resolution data transmission from downhole (Hall and Fox, 2002) exist together with "along string measurements" (Reeves et al., 2011). This means that simple models that can be combined with real-time measurements are particularly needed for creating suitable control systems.

The general model is outlined in Section 2 and the model for torsional vibrations while reaming is given in Section 3. The detection algorithm is included in Section 3. Calculations on a J-well is given in Section 4, where a sensitivity study of the detection algorithm is included. A discussion is added in Section 5, while the paper is concluded in Section 6. A nomenclature is added at the end of the paper.

2. Dynamic model for the drillstring in a deviated wellbore

We consider a drillstring that is modeled as a set of n blocks that are connected by n spring elements, see Fig. 1. A three-dimensional coordinate system is introduced. The first block is hanging from the first spring which is attached to a point that is called the "block position". This point has the coordinates $\{0,0,0\}$. The coordinates of the blocks are denoted $\boldsymbol{X}_{s,i}$ and the wellbore geometry is defined by a set of n normalized tangent vectors, such that $\boldsymbol{\nu}_1=\{0,0,-1\}$ and $\boldsymbol{\nu}_i=(\boldsymbol{X}_{s,i}-\boldsymbol{X}_{s,i-1})/h$ for $2\le i\le n$, where $h=|\boldsymbol{X}_{s,i}-\boldsymbol{X}_{s,i-1}|$.

The springs are fixed to the blocks, meaning that the springs can take up angular momentum. The drillstring can be rotated clockwise and the rotation angle at the block position is $\Theta(t)$, where the initial condition $\Theta(0)=0$ is always assumed. Each block is rotated clockwise by an angle $\theta_i(t)$ around $\boldsymbol{\nu}_i$ and the physical state of the drillstring uniquely defined by the generalized coordinates $\theta_i(t)$.

By combing Newton's second law with Hooke's law we obtain

$$\begin{aligned}
&0=I_1\ddot{\theta}_1+\kappa_1(\theta_1-\Theta)-\kappa_2(\theta_2-\theta_1)-S_1\\
&0=I_i\ddot{\theta}_i+\kappa_i(\theta_i-\theta_{i-1})-\kappa_{i+1}(\theta_{i+1}-\theta_i)-S_i \qquad 2\le i\le n-1\\
&0=I_n\ddot{\theta}_n+\kappa_n(\theta_n-\theta_{n-1})-S_n,
\end{aligned} \tag{1}$$

where for block i, I_i is the moment of inertia, κ_i is the spring above the block and S_i is the external torque.

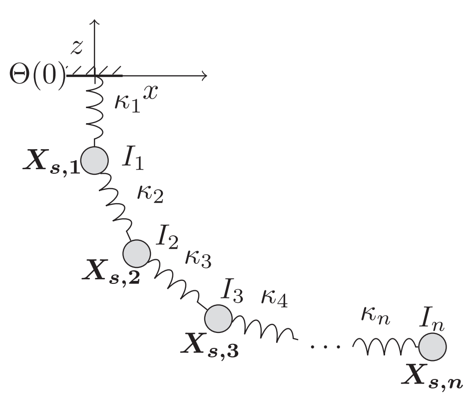

Fig. 1. Schematic view of the model of the drillstring. The drillstring is considered as a set of n blocks with masses and moment of inertias denoted by m_i and I_i, respectively. These blocks are connected to n springs with spring constants that are denoted with κ_i.

2.1. Friction forces from the fluid

We model the viscous friction forces on the drillstring as a sum of two groups of forces. These are the steady-state friction forces and the Basset forces, which are the forces that are dependent on the time history. When the rotation speed is constant, we assume a Newtonian laminar flow and the velocity profile is

$$u_i(r)=C_1r+\frac{C_2}{r},$$

where C_1 and C_2 are constants that are determined by the boundary conditions $u_i(R)=0$ and $u_i(\alpha_iR)=\alpha_iR\dot{\theta}_i$ (Stokes, 1845). Here, α_i is the radius of the drillstring at element i, divided by the hole radius R. We easily see that $C_1=-\alpha_i^2\theta_i/(1-\alpha_i^2)$ and $C_2=-C_1R^2$. The shear stress on the wall is given by $\mu\partial u_i/\partial r$ at α_iR, where μ is the fluid viscosity. We therefore conclude that the steady-state friction torque $S_{ss,i}$ is

$$S_{ss,i}=2\pi\alpha_i^2R^2h\mu\frac{\partial u_i}{\partial r}\bigg|_{\alpha_iR}=-c_{ss,i}\dot{\theta}_i \quad \text{where} \quad c_{ss,i}=2\pi R^2h\mu\frac{\alpha_i^4+\alpha_i^2}{1-\alpha_i^2}.$$

The Basset forces are related to the fact that the steady-state velocity profile is not developed when the rotation is accelerated. In order to model these forces, we exploit a result that is given in Langlois and Deville (2014). In the case of an infinite container of fluid, which has an infinite horizontal plate that suddenly moves with a speed U, the velocity profile in the fluid is

$$u(t)=U\left(1-erf\left(\frac{y\sqrt{\mu}}{2\sqrt{\rho_mt}}\right)\right),$$

where y is the vertical direction. Moreover, in the situation of time-dependent U, it is shown in Langlois and Deville (2014) that the accumulated effect on the shear stress is

$$\sqrt{\frac{\rho_m\mu}{\pi}}\left(t^{-\frac{1}{2}}*_t\frac{\partial U}{\partial t}\right),$$

where $*_t$ denotes the convolution with respect to time. We let $U=\alpha_iR\dot{\theta}_i$ and we suggest that the Basset torque $S_{ba,i}$ on the drillstring is

$$S_{ba,i}=2\alpha_i^3R^3h\sqrt{\pi\rho_m\mu}\left(t^{-\frac{1}{2}}*_t\ddot{\theta}_i\right)=b_i\left(t^{-\frac{1}{2}}*_t\ddot{\theta}_i\right). \tag{2}$$

Paper (Hovda, 2018a) explains the dynamics on the axial motion in the drillstring when these forces are action on it. Different from that paper we will also add Coulomb friction forces $R_{i,co}$.

2.2. Coulomb friction forces

Coulomb friction states that the friction force between two sliding surfaces is proportional to the normal force with a direction that opposes the motion. Similar to Hovda (2018b), we assume that the normal forces are dominated by the tension forces due to the drillstring weight. We neglect the effect that axial vibrations have on the normal forces.

It is essential in the Coulomb friction model to determine the absolute values of the normal forces that are acting on the blocks. To establish these normal forces, we define n normal vectors $\boldsymbol{n}_i$, which are basically the derivative of the tangent vectors with respect to the length of the arc. They are defined as

$$\boldsymbol{n}_i=\begin{cases}\{1,0,0\} & \text{for} \quad i=1 \quad \text{or} \quad \boldsymbol{\nu}_i=\boldsymbol{\nu}_{i+1}=\{0,0,-1\}\\ \boldsymbol{\nu}_i\times(\boldsymbol{\nu}_i\times\{0,0,-1\}) & \text{for} \quad i\ge2 \quad \text{and} \quad \boldsymbol{\nu}_i=\boldsymbol{\nu}_{i+1}\ne\{0,0,-1\}\\ \dfrac{\boldsymbol{\nu}_{i+1}-\boldsymbol{\nu}_i}{|\boldsymbol{\nu}_{i+1}-\boldsymbol{\nu}_i|} & \text{for} \quad i\ge2 \quad \text{and} \quad \boldsymbol{\nu}_i\ne\boldsymbol{\nu}_{i+1}.\end{cases}$$