Modeling and experimental validation of axial drill string dynamics

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1 Introduction

In the analysis of torsional stick-slip vibrations in drilling systems using drag bits, the drill string model is generally limited to the torsional dynamics. Herein, the bit-rock interaction is often modeled as a velocity-weakening friction law, which leads to torsional (stick-slip) vibrations. However, bit-rock interaction experiments using single cutters have not revealed any intrinsic velocity-weakening effect, suggesting that this effect is likely to be the result of complex drill string dynamics. This insight led to a different modeling approach, introduced in [3]. Here, the axial and torsional dynamics of the drill string are coupled via a rate-independent bit-rock contact model [1]. Analysis of this model shows that fast self-excited axial vibrations lead to an apparent velocity-weakening effect in the torsional direction [2], causing torsional vibrations and stick-slip.

In this presentation, the focus will be on the experimental validation of the axial dynamics of the model as proposed in [3] and analyzed in [2].

2 Experimental validation of the axial dynamics

In [2], it was shown that the fast axial dynamics can be analyzed separately because of the separation of time scales between (fast) axial and (slow) torsional dynamics. Further, self-excited axial vibrations are shown to be the driving force behind an apparent velocity-weakening effect.

Figure 1: Experimental setup "TAZ", representing axial drill string dynamics (left) and rock sample and cutter detail (right).
in the torsional dynamics, ultimately leading to torsional stick-slip vibrations. To experimentally validate these results, a test rig involving a mechanical equivalent of the axial dynamics was built at CSIRO, Australia. The experimental setup, named TAZ, is depicted in Figure 1 and consists of a rotating sandstone disk on which a cutter can be lowered. During cutting, both the vertical position and the cutting forces are measured, as well as the rock profile. Experiments under constant weight-on-bit reveal discrepancies between the experimental results and the dynamics predicted by the model, suggesting that the bit-rock interaction model is incomplete.

Additional experiments, where the axial position $U$ of the bit is under kinematic control, therefore aim to model the bit-rock contact, focusing on the contact between the rock and the underside of the cutter. This contact area is caused by wear of the cutter and is referred to as the wearflat. In the bit-rock interaction model used in the model of the axial dynamics in [2], a discontinuous behavior of the contact forces with respect to the axial velocity $dU/dt$ is assumed, as depicted in Figure 2. However, a smooth transition between contact and loss of contact is found experimentally. Figure 2 illustrates this experimental fact for the normal forces, whereas the parallel forces show a similar trend. This transition is dependent on the geometry of the contact, as characterized by the approach angle of the cutter. The approach angle is defined as the angle of the velocity vector with respect to the forward motion, as defined in Figure 3. Further, the contact forces are dependent on the depth-of-cut. Based on these results, the bit-rock interaction model is updated, using a piecewise linear approximation for the wearflat forces, as depicted in Figure 2. Simulations using this updated bit-rock interaction model show a significant improvement when comparing the experimental results with the theoretical predictions.

Finally, the updated bit-rock interaction model is implemented in a full drill string model, including the torsional dynamics. Preliminary analyses of this model show two distinct regimes. First, for small nominal approach angle, corresponding to a low rate-of-penetration, the axial dynamics is locally asymptotically stable and no torsional vibrations occur. In this regime, the normal bit-rock contact forces are proportional with the approach angle, causing an apparent damping in the axial dynamics that stabilizes the axial equilibrium point, which corresponds to a constant downward velocity of the drill bit. Second, for a higher nominal approach angle, the axial dynamics is unstable, leading to axial limit cycling, which in turn causes an apparent velocity
weakening effect in the torsional dynamics. In this regime, the velocity weakening effect causes torsional vibrations and torsional stick-slip, which is similar to the results predicted by the original model as in [2].

3 Conclusions

The drill string dynamics model analyzed by [2] is validated experimentally. Initial experimental results using a mechanical equivalent of the axial dynamics indicate that the bit-rock interaction model is incomplete. Additional experiments are performed to identify the bit-rock interaction in detail, focusing on the contact forces under the wearflat. Based on these results, the bit-rock interaction model is updated and implemented in a full drill string model. Preliminary analyses of this model show two distinct regions, of which one leads to torsional stick-slip oscillations.

Since the bit-rock interaction is the driving force behind drill string dynamics, future work will focus on additional experiments for the identification of the bit-rock interaction law in more detail.

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References

