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The Potential of HIL-Simulations for the Optimization of Deep Geothermal Wells

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Abstract

The development of geothermal energy resources requires a high level of drilling technology. In addition to the challenging environmental conditions (high temperatures and pressures), especially downhole vibrations, which are excited by the drilling process itself, have a negative influence on the rate of penetration and wellbore quality. The drilling process in hard rock and rock homogeneities as well as fault zones, which are drilled in deep geothermal wells, excites a number of vibration phenomena on the bit, such as stick-slip vibrations, high-frequency torsional vibrations or whirl phenomena.

Due to the large length/diameter ratio, entire drill strings cannot be tested in hardware without considering the limitations of similarity mechanics. This is exactly why HIL-simulations are applied. For example, the bottom hole assembly (BHA) can be represented in hardware and the drill string itself is described simulatively using suitable mathematical models. Thus, the BHA becomes a full-scale test stand via the virtual addition of the drill string, whereby the BHA is integrated into the simulation models as hardware using suitable HIL-control algorithms. In this paper, the procedure is explained using an example of a stick-slip vibration of the drill string. In addition, the influence of rock inhomogeneities on drill string dynamics is investigated and discussed.

HIL-simulations provide a realistic simulation of the drilling process and drill string dynamics in the test stand. With this procedure a tool is created that can be used to optimize the drilling process of deep geothermal drillings.

1. Introduction

Within the collaborative project “OBS – Optimization of the Rate of Penetration for Deep Geothermal Wells through Systematic Analysis of Downhole Vibrations in Lab Tests” a HIL-simulator will be designed to investigate and analyze the drill string dynamics under deep geothermal boundary conditions. The goal is to optimize the drill string setup and the drilling process itself for an optimization of the rate of penetration under hard rock conditions as well as in rock inhomogeneities and fault zones. Therefore, IDS is working on the subproject “Vibration Behavior and Dynamic Processes of Bottom Hole Assemblies” and is developing appropriate models and simulation techniques to control the HIL-Simulator. The hardware part of the HIL-Simulator will be designed and assembled at the DSC in Celle. The basic idea of this project considers a real drilling system as shown in Fig. 1 [3, 4]. With a cut, this system is divided into two parts. The upper part is modeled in software (IDS), the lower part in hardware (DSC) – in this case a BHA specimen in the test stand with a pipe system representing the well bore in the lab. The HIL-Simulation will be controlled via the virtual drill model by an interface. The procedure can be briefly described as follows: At the time t the software model computes the complex geometry of the drill string by given forces. The next step is to realize this geometry via actuators in the interface on the test stand. The reaction forces of the test stand will be measured by sensors and these forces are again the input of the software model in the next time step in closed loop manner.

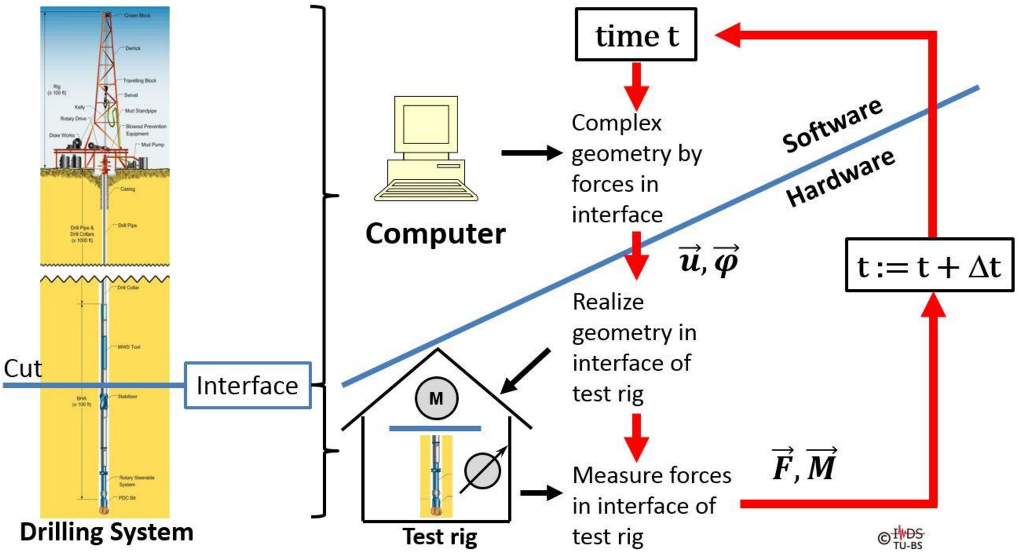


Fig. 1: HIL-Simulation for deep drilling systems – initial idea and concept [3, 4]

This paper focuses on the software part of the HIL-Simulator and, in particular, on the modeling, simulation and HIL-control strategies.

2. Modeling and HIL-Simulation Strategy

The following strategy is pursued in the modelling process: As the real system of the drill string is quasi unobservable (apart from the process data at the drilling rig, data are only available selectively in the area of the bottom hole assembly in limited time intervals), a suitable approximation of the real system is required. Therefore, arbitrary wells for the exploration and exploitation of deep geothermal energy must be approximated using suitable complex models. The basis for this is the modeling of the simulation tool OSPLAC [1] that is being further developed for research purposes and provides a simulative description of the dynamics of complex drill strings in arbitrarily curved boreholes in time and frequency domain. The model is described by the following equations of motion

$$\underline{\underline{M}}\,\underline{\ddot{q}} = \underline{F}\left(t,\underline{q},\underline{\dot{q}}\right), \quad \underline{q} = (q_1,\dots,q_n)^T \tag{1}$$

The OSPLAC tool models the drill string as a nonlinear FE model, in which sub-models for the bit and for dissipation mechanisms, such as impact-like contacts between drill string and borehole, are integrated. Of course, for HIL-simulations real-time capable models are necessary to control the process. Thus, first virtual real-time drill string models have been developed using suitable reduction techniques, which are especially tailored to the current actuators at the DSC. These models simulate the drill string dynamics in real time with the nonlinearities due to the bit-rock-contact. The reduced equations of motion can be written in the form

$$\underline{\underline{M}}\,\underline{\ddot{q}}_{red} = \underline{F}_{red}\left(t,\underline{q}_{red},\underline{\dot{q}}_{red}\right) + \underline{G}_{nl}(\dots), \quad \underline{q}_{red} = (q_1,\dots,q_m)^T \quad, m \ll n \tag{2}$$

wherein $\underline{G}_{nl}(\dots)$ covers event-controlled nonlinear terms, which are caused, for example, by the aforementioned interactions between the drill string and the borehole. A suitable numerical approach of these terms is subject of current research work. Because the test stand itself, including the BHA specimen with actuators, has its own dynamics, suitable real-time models must also be developed for this purpose. This parasitic dynamic does not exist in the real drilling system and must be compensated in the HIL-simulation.

In order to perform realistic drilling tests, the drilling process in the test stand is controlled by the models of drill string and test rig in the HIL-simulation. Figure 2 shows schematically how the software models interact with each other and with the hardware of the test stand.
For this purpose, four models have been developed, whose model-depth varies in complexity and degree of abstraction depending on the task definition. The model M0 describes the complex, not real-time capable entire model of the drill string in arbitrarily curved boreholes and is a further development of the OSPLAC model, eq. (1). It is the basis of the reduction and used for validation. From this complex drill string model, a real-time-capable entire model of the drill string, the model M1, with suitable reduction techniques is derived for the HIL-simulation. The model M2 is also real-time capable and describes the bottom hole assembly that is driven by an actuator. The test stand itself is described by the model M3 in order to simulate the parasitic dynamics occurring from the test stand during the drilling tests.

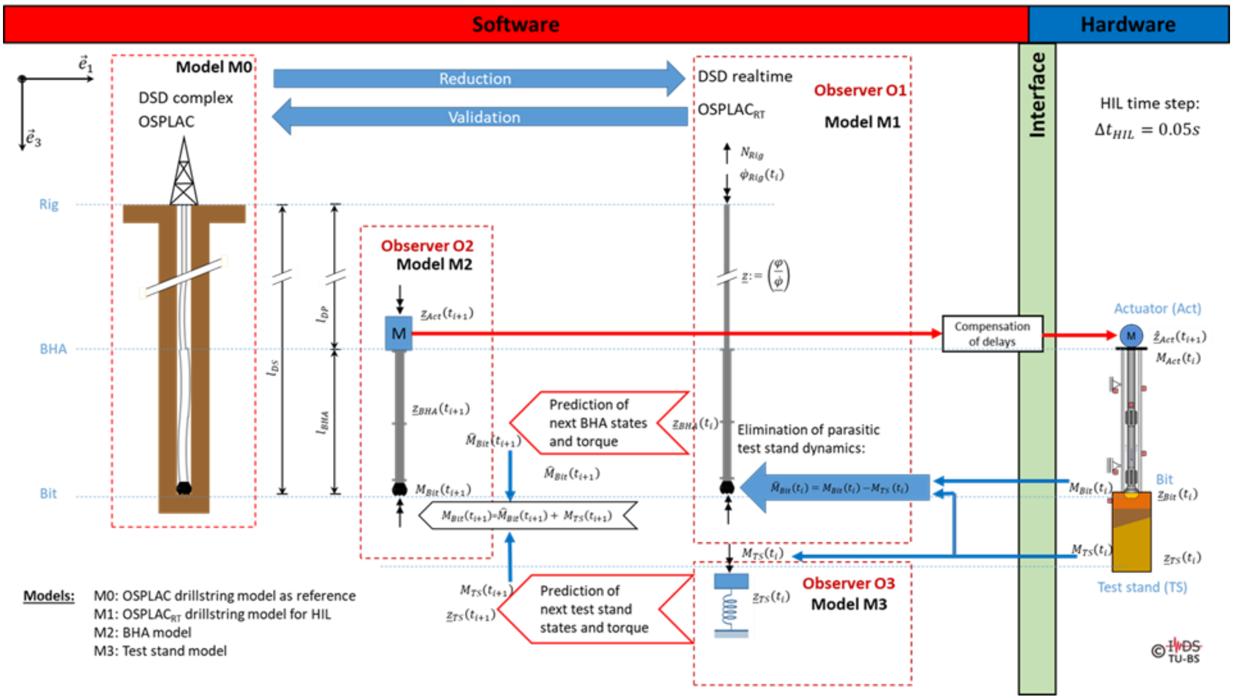


Fig. 2: Schematic diagram of linked models for HIL-simulation

Thus, the HIL-simulation consists of a software part, in which the real-time models M1, M2 and M3 as well as the Observer O1, O2 and O3 are processed, and a hardware part, the test stand at DSC including actuators and sensors. Software and hardware are coupled via an interface and interact in a closed loop, see Fig. 2. Force and/or state variables of the specimen and test stand are measured on the test stand during the HIL-Simulation. In most cases, the measurements are only selective and only a few elements of the state vector can be observed. An observer is necessary based on the real-time capable test stand model M3. This observer O3 receives the measured values at the test stand and reconstructs the state vector. The measured values at the BHA-specimen are compensated by the parasitic test stand dynamics and transferred to the real-time capable drill string model M1 and its state vector is calculated (O1). After the reconstruction of the state vectors of the BHA-specimen and the test stand, the prediction of the future state vectors based on the models M1 and M3 is necessary to ensure a stable HIL-simulation. The predictive observers O1 and O3 estimate the state and force variables of the BHA-specimen and test stand. The state vector from the BHA-specimen contains the prospective behavior of the BHA without parasitic dynamics of the test stand and should be realized in the hardware in the next step. Therefore, this vector is transferred from the entire model M1 to the specimen model M2. As the hardware still has parasitic dynamics, prospective information from the test stand are also transferred to the model M2. Thus, the observer O2 receives the predicted BHA state without parasitic dynamics in the form of a state vector and predicted forces/moments including the influence of the parasitic dynamics of the test stand. The model M2 in the observer O2 contains also the mechanical model of the actuator besides the BHA model. Here, the state vector of M2 is reconstructed to calculate the torque/force and/or state of the actuator. These prospective nominal values from the actuator are transferred to the test stand in the next HIL-time step. On the hardware part, inertia and delay times of the actuator have to be compensated.

The basic functionality of this HIL-simulation principle is explained in the next section using the example of a stick-slip simulation.

3. Simulation Results

In this section, two simulations and their results are presented and discussed. Firstly, the HIL-strategy introduced above is described using an example of a stick-slip simulation. The simulation results will demonstrate the necessity of a model control for realistic tests. Secondly, the dynamics in the drill string due to rock homogeneities are investigated. The relevance for the implementation in a HIL-simulator here becomes clear as well.

As introduced, a nonlinear FE model for the simulative analysis of the dynamics is used, that is implemented to in-house software tool OSPLAC [1], whereby the number of degrees of freedom per node can be adjusted according to the investigated issues.

3.1 Stick-Slip Simulation

A detailed introduction to stick-slip and mode coupling phenomena was presented in [5]. For modeling the bit aggressiveness, a falling friction characteristic is assumed. Fig. 3 (left) shows the animation plot of an exemplarily drill string. One can see the rotation of the drill string around its longitudinal axis. The angular velocity at the rig is constant at the BHA (approximately 40 m from the bit), the angular velocity varies as shown according to the stick and slip phases.

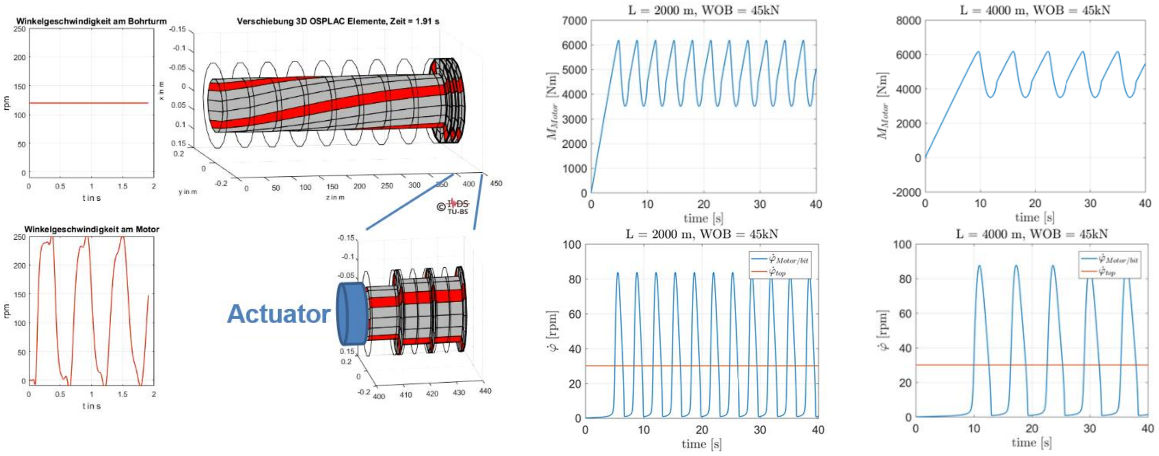


Fig. 3: (left) Animation plot of an exemplary drill string and angular velocities at rig and BHA/bit, (middle) and (right) simulation results for variation of drill string lengths at given constant speed at rig and given WOB

In Fig. 3 (middle, right) the angular velocities and the torsional moments are shown for different drill string lengths, constant RPM at Rig and constant WOB. It is obvious that the stick and slip phases increase as the drill string becomes longer with respect to the length-dependent elasticity of the drill string. Fig. 4 shows that stick-slip in a full-scale simulator is not possible without model control of the actuator. Here, the length of the drill string over the first torsional natural frequency is plotted double-logarithmically. It is obvious that the first torsional natural frequency of the BHA specimen is significantly higher than the first natural frequency of real drill strings in the field.

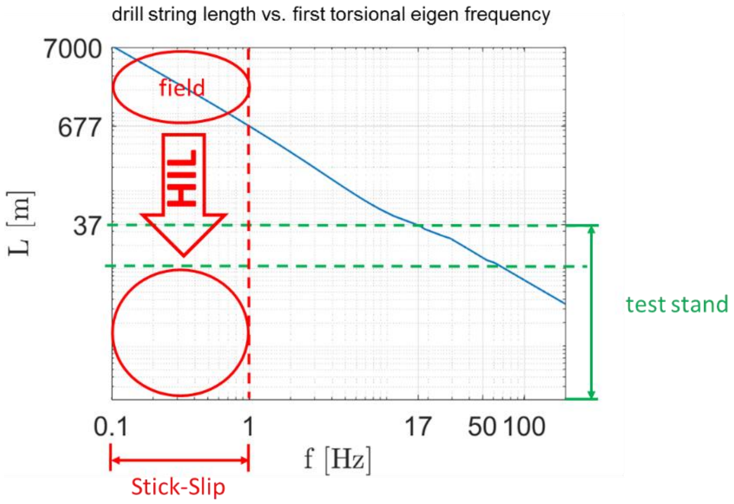
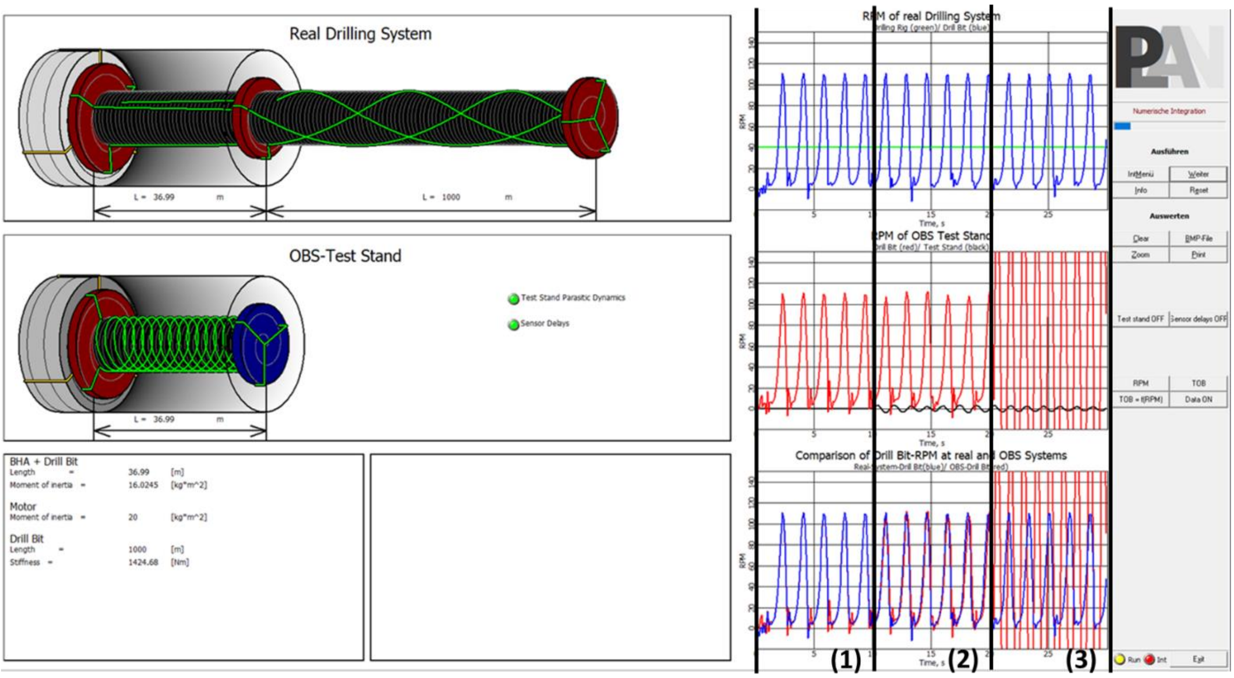


Fig. 4: Stick-Slip implementation on a HIL-Simulator

In order to be able to perform realistic HIL-simulations, the actuator of the included Hardware-BHA, as shown in Fig. 3 (left), must simulate the dynamics of the entire drill string in a test stand. This includes the application of HIL-control strategies to compensate delay times from sensor data recording and processing, actuator control and the influence of parasitic test stand dynamics. In order to test these strategies on a simulation model, a virtual model for the HIL-Simulation has been developed, see Fig. 5. Thereby, the hardware is emulated by a software model.



BHA + Drill Bit
Length = 36.99 [m]
Moment of inertia = 16.0245 [kg*m^2]

Motor
Moment of inertia = 20 [kg*m^2]

Drill Bit
Length = 1000 [m]
Stiffness = 1424.68 [Nm]

Fig. 5: Virtual model of HIL-Simulation (hardware is emulated by a software model)

Fig. 5 shows the simulation results. Phase (1) shows the case that the subsystem of the BHA responds exactly as it is required by the entire drilling system. However, a borehole design in the test stand is not rigid as the borehole downhole. Phase (2) shows the influence of additional test stand elasticity. This parasitic test stand dynamics must be compensated in the HIL-simulation. If the delay times from sensor data recording and processing and actuator control are not compensated, the system becomes unstable as shown in phase (3). Using this virtual model of the HIL-Simulation, we are able to develop predictive intelligent HIL-control algorithms to avoid this delay times and to compensate parasitic dynamic effects.

3.2 Drilling through Rock Inhomogeneities

To estimate the dynamics in inhomogeneity zones, the drill string configuration from Fig. 6 was exemplary used with a drill string length of L_{DS} = 1000m and a BHA length of L_{BHA} = 35m corresponding to the OBS-project. As mentioned above the Hardware-BHA will be controlled by virtual drill string models via HIL-Simulation techniques with respect to the entire drill string dynamics. Simulation studies are performed for the design of realistic tests in which the bit drills into two rocks of different strengths and lengths. The transition phase, the most important zone during these examinations, consists of a variable length $L_{1/2}$ which depends on the inclination angle α (45° or 89° in this study) and the outer diameter D of the bit. Due to the small drilling depth (max. 4.5m) compared to the total initial length L of the drilling system, L can be assumed constant. The entire drill string is driven by constant RPM and ROP (60rpm, 10m/h). The WOB was also kept constant. The boundary conditions in the torsional direction are assumed free on both sides while the lateral direction is fixed at the top and supported at the bit.

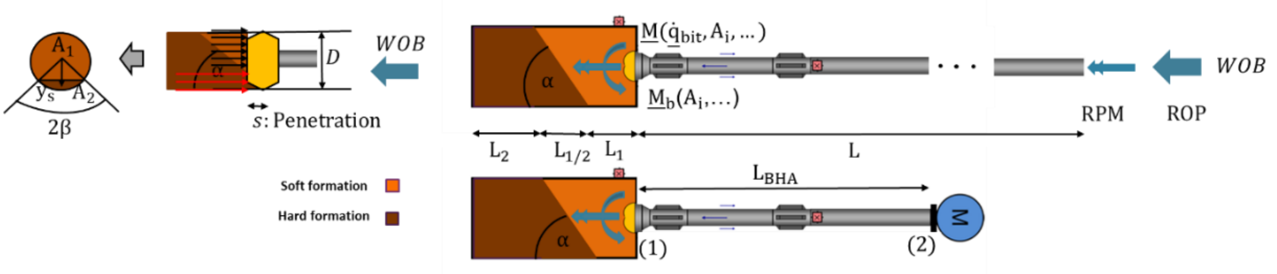


Fig. 6: Schematic overview of the drill string configuration with additional moments due to the rock inhomogeneity in lateral ($\underline{M}_b$) and torsional ($\underline{M}$) direction

The equation of motion of the system is given by eq. (1). The addition of a force vector $\underline{F}_a\left(t, \underline{q}, \underline{\dot{q}}\right)$ that takes into account additional moments, $\underline{M}(\underline{\dot{q}}_{bit}, A_i, E_i, \ldots)$ and $\underline{M}_b(A_i, E_i, \ldots)$, due to the rock inhomogeneity, yields to

$$\underline{\underline{M}}\,\underline{\ddot{q}} = \underline{F}\left(t, \underline{q}, \underline{\dot{q}}\right) + \underline{F}_a\left(t, \underline{q}, \underline{\dot{q}}\right), \quad \underline{q} = (q_1, \ldots, q_n)^T \qquad (3)$$

The torsional moment at the bit $\underline{M}(\underline{\dot{q}}_{bit}, A_i, E_i, \ldots)$ is determined based on the bit-rock-interaction described by a falling torque characteristic of the contact torque with respect to the angular velocity of the bit and is calculated depending on the frictional area between the bit and different rock formations. The bending moment at the bit $\underline{M}_b(A_i, E_i, \ldots)$ is the result of a change in the stiffness characteristics at the contact between bit and rock due to the rock inhomogeneity [6].

During the simulation studies two positions of the drill string will be observed and analysed: (1) the bit and (2) the BHA at the actuator position of the test stand, see Fig. 6. The torque at position (2) is low and constant in the soft formation, Fig. 7 (left). But the torque increases while drilling in the hard formation and runs into a stick-slip cycle (<1Hz). Fig. 7 (right) shows the RPM at position (2) and at the top of the rig. The first 0.5m are drilled in soft rock. After about 100s, the bit/BHA rotates at constant speed. Due to the inhomogeneity, the bit begins to be instable and stick-slip occurs while drilling the hard formation.

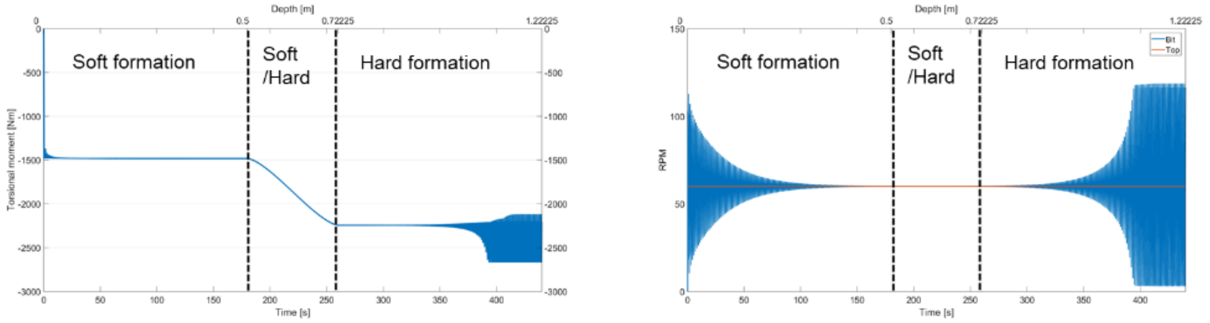


Fig. 7: Rock inclination of 45°, results of torsional dynamics, (left) torsional moment on the bit, (right) RPM at bit and rig

Considering the lateral dynamics, in Fig. 8 (left) the bending moment depends on the homogeneity, see soft/hard phase. As expected, this leads to high-frequent lateral vibration at the actuator position, see Fig. 8 (right).

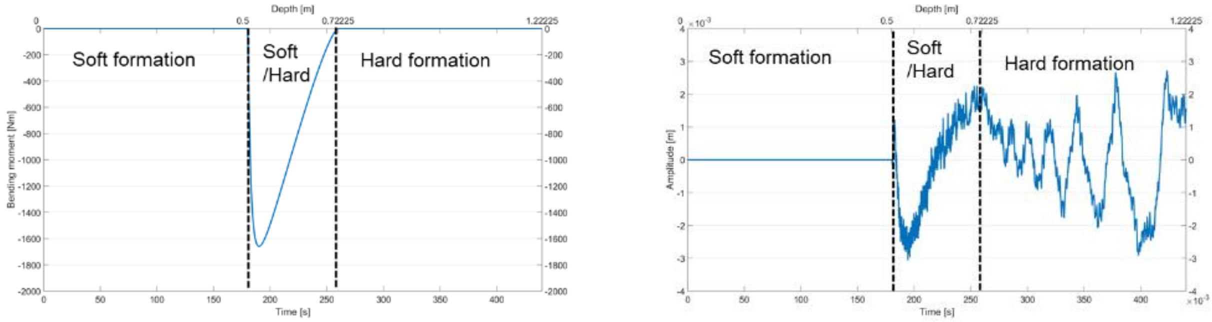


Fig. 8: Rock inclination of 45°, results of lateral dynamics, (left) bending moment on the bit, (right) lateral amplitude at actuator position

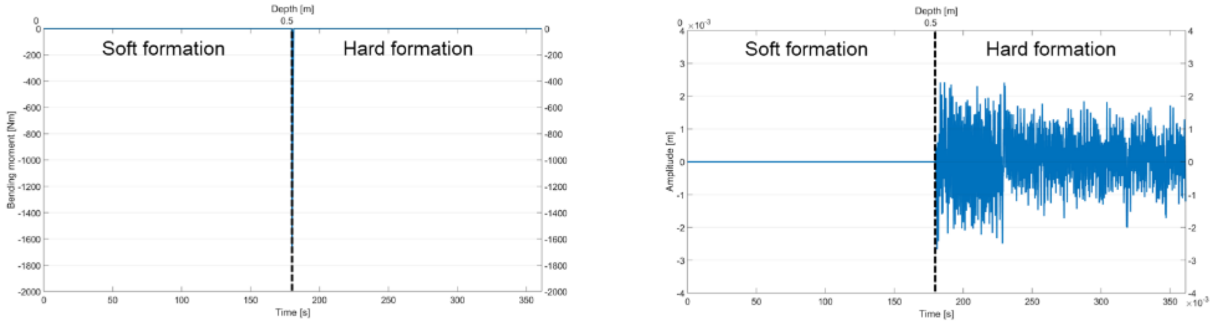


Fig. 9: Rock inclination of 89°, results of lateral dynamics, (left) bending moment on the bit, (right) lateral amplitude at actuator position

Fig. 9 shows that even an infinitesimal small inhomogeneity phase causes a shock-like bending moment on the bit that leads to lateral dynamics of the entire drill string and the BHA. These lateral dynamics must also be able to be modeled in a HIL-test stand using suitable actuators. These first investigations on the influence of rock inhomogeneities on the drill string dynamics already show the required performance of a HIL-test stand in order to be able to perform realistic simulations.

4. Conclusion and Outlook

This paper has introduced basics of HIL-Simulation for drilling simulators. Using the example of a stick-slip vibration of drill strings, influencing parameters and the implementation in HIL-simulations are discussed. The virtual HIL-strategies presented here are currently being implemented and tested on a laboratory scale drill string demonstrator (OSTrator [2]). The developed models and control strategies can then be scaled and implemented to full scale test stands (e.g., OBS test stand at Drilling Simulator Celle). Further simulation studies have shown which fundamental impact formation changes with inclination and fault zones have on the drill string dynamics. The resulting vibration phenomena are manifold and are to be validated with measurement data from field test and test stands. For realistic drilling tests, it is also essential to be able to simulate lateral and longitudinal motions in a HIL-simulator.

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