The drilling industry is steadily moving towards automation. To have a better control over the drilling operation and to optimize the drilling performance, it is necessary to have a good understanding of the physics involved in the process. A good simulation model of the drilling process/system would be of great value in assisting this and in enabling the development of strategies to optimize it.

A representative simulation model can provide insights into various phenomena that appear during drilling for different drilling conditions. Such a model is also likely to be of assistance in preparing various measurements. Issues such as choosing the type of sensors, their positions and which quantities to measure are supported by a model. A well calibrated model in combination with information extracted from measured data are hence likely to assist in selecting control strategies for optimized drilling performance.

In this paper we present a MATLAB based 1D simulation model of a Down The Hole (DTH) drill and compare it with an existing 1D model in terms of computational speed and accuracy. The emphasis is to make a 3D model of a DTH system that is computationally efficient and accurate.

1. Introduction

Today the drilling industry strives towards automation and optimization of the drilling process. Energy and process efficiency requirements are the key factors in driving this progression [2].

For the work to be successful, it is important to understand the physics involved in the drilling process to enable the development of an efficient monitoring system. Such a system should provide reliable information enabling control of the drilling parameters with the purpose of optimization and automation of the drilling process.
To understand the physics, it is very important to develop representative simulation models of the DTH drilling system. It will not only facilitate the understanding of the system but also provide guidance for experimental set-ups and indirectly support the selection of the signal processing strategy regarding suitable algorithms for monitoring and control.

1.1 Drilling process.

The DTH drilling is a percussive process where the hammer operates down the hole as opposed to top hammer drilling where the hammer process is carried out at the top of the drill string, above the ground, see Fig. 1. The piston is inside a casing which is screwed on to a hollow drill pipe which in turn is pushed down the hole while drilling. Successively, pipes are screwed on to the top end of each drill pipe that has been pushed completely under the ground level.

The hollow drill pipes/tubes carry work fluid, which in most cases is air but may also be water. In the DTH drill, the compressed working fluid passes to different chambers in the casing containing the piston. The pressure on different areas of the piston due to the fluid pressure in different chambers causes alternating motion of the piston. The movement of the piston also opens and closes different pathways through which the chambers are filled with the working fluid. The pressurized fluid is also pushed through the bit in order to remove the debris. This process is known as flushing.

The drilling process is briefly illustrated in Fig. 2. The impact is shown in a), the drill bit and the drill tube are then in contact. The drill tube rests on the shoulder of the drill bit. Soon after the impact the drill tube separates from the drill bit as the drill bit penetrates the rock, which is illustrated in Fig. 2b). The feed force, represented by the red arrow in Fig. 2b), pushes the drill tube back towards the drill bit and the tube meets the bit as shown in the Fig. 2 c). Subsequent, the piston is pulled upwards away from the bit by the hydraulic pressure acting on area A2 in Fig. 2. c) and the piston travels away from the bit and compresses the air in the chamber above it. This causes the fluid in the upper chamber to be over pressurized and the working fluid acting in the upper chamber pushes the piston back towards the bit as shown in Fig. 2d).

![Figure 1: Down The Hole (DTH) and Top Hammer Drilling process.](image-url)
2. Overview of Different modelling techniques for DTH system.

The Bit-Rock interaction is the most modelled and studied behaviour of a DTH drilling system. As DTH systems are substantially more complex compared to e.g. top hammer systems; complete DTH drilling systems are generally not modelled or simulated.

Different models representing the wave propagation in the drill bit and the piston of DTH systems are available. The Bit-Rock interaction is analysed using penalty functions i.e. using relations between the force exerted onto the rock and the penetration distance of the drill buttons. In order to study the bit rock interaction, numerous rock models have been developed in both the 1D domain and the 3D domain.

3. 1D model

A 1D model is often the first, or basic, model that is developed with the purpose to increase the understanding of a system. It has the advantage over a 3D model in terms of computational speed particularly when more than one kind of physics is included in the model and a 1D model also tends to have lower complexity.

On the other hand it becomes difficult to understand or implement multi-dimensional phenomena using 1D models. The knowledge gained through the analysis of simple 1D simulations can be utilized to make more complex models and ultimately better 3D models.

3.1 Study of Dynamics

A 1D model of a DTH system is used to study the dynamics and to understand the relative motion between different components of the system. The relative motion of the bit and hammer and motion of the drill tube constitute the main interest of this study.
3.1.1 Modelling of the DTH system

It is important to understand the drilling cycle to understand how different components behave relative to each other, so that an accurate model can be made.

At the start of the DTH drilling cycle, the drill bit, the rock and the drill tube are assumed to be in contact and at rest. The piston impact forces the bit to penetrate into the rock. This cause the drill tube to lose contact with the shoulder of the bit. The upward motion is counteracted by the feed force and gravity acting on the drill tube which push it back towards the shoulder of the bit. When the drill tube meets the shoulder of the bit again and the rock chips formed are flushed away.

After the bit has penetrated into the rock due to the piston impact, the bit will bounce up slightly from the compressed rock. This will cause the piston to bounce of the bit and it is carried away from the bit by the hydraulic pressures acting on the lower areas of the piston for the next impact.

To model the dynamic properties of a DTH system and thus enable the simulation of the motion of the drill tube, bit, piston, etc. the equation of motion of the DTH system may be formulated in terms of a multiple-degrees-of-freedom (MDOF) system. The equation of motion for an MDOF system in matrix form can be written as:

\[
[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{f(t)\}
\]  

(1)

Where \([M]\) is the NxN mass matrix, \([C]\) is the NxN damping matrix, \([K]\) is the NxN stiffness matrix, \([x(t)]\) is the Nx1 displacement vector and \([f(t)]\) is the Nx1 load vector.

The rock is modelled as a nonlinear spring with stiffness \(k_1\) in compression and stiffness \(k_2\) in decompression [1]. All the other components of the DTH system are modelled in terms of sub-MDOF systems consisting of multiple masses connected with springs which together equals the component’s elastic stiffness. The feed force is modelled as a constant force at the top of the Drill tube. Piston motion is actuated by forces equivalent to the hydraulic forces that drives the piston. The interactions between the bit and the other components are modelled using springs with estimated contact stiffnesses.

After every cycle of impact the Rock is shifted a distance equivalent to the penetration depth of the bit. A schematic diagram of the model is shown in Fig.3.

The derived MDOF model of the dynamic properties of the DTH system is simulated in MATLAB using the ODE45 functions.
Figure 3: Schematic representation of the model implemented in MATLAB.

4. **3D Model concepts.**

The greatest challenge in the 3D modelling of a DTH drilling system is the inclusion of the rock as a boundary condition. Usually the rock is included as a spring with different stiffness values for compression and decompression. Unlike the 1D model where it is easy to implement a spring connected to the bit, in a 3D model it is not so intuitive how this can be achieved without the knowledge of how the stiffness should be distributed among the different buttons on the bit.

There exists comprehensive 3D rock models for specific rock types that has been used for studying the Bit, Hammer, Rock interaction [1]. Such models are computationally very expensive, more so if it is intended to model the drill tube etc. to simulate multiple impacts.
5. Results.

5.1 The Motion of the Drill Tube.

Results, from the 1D simulation, of the displacement of the bottom of the drill tube is shown in Fig.4.

The drill rate is approximately 4 times faster compared to real DTH drilling. After the drill button has penetrated the rock DTH drilling, the drill string is rotated to move the buttons from the indentation in the rock to rock that is not fractured for the next impact.

5.2 The motion of the drill bit and the Piston (Hammer).

Figure 4: Displacement of the drill tube as a function of time.

Figure 5: The position of the bottom of the piston and the drill bit as functions of time.
Figures 5. & 6. show the position of the drill bit and the piston bottom during a simulated drilling process. The drill bit position displays a chatter pattern because of the effect of the rock, which is modelled as a spring. Figure 6. shows the interaction of the piston with the bit during a simulated drilling process. The piston impacts with the bit and remains in contact with the bit for a short period of time and then bounces back and travels away from the drill bit.

6. Factors affecting the simulation.

Major factors that influence the outcomes of the simulations are the rock characteristics i.e. the stiffness in the compression and decompression phases. The feed force also has a substantial influence on the outcome of the simulations. A low feed force causes the drill tube to show an overly jumpy behavior in the simulations.

The damping in the chambers is also a factor that influence the motion of the piston and determines its velocity, stroke length and in general interaction with the bit.

In reality, there are a large number of factors that affect the motion of the drill tube. For instance, the different hydraulic chambers may add damping to the system and the rock itself may also provide damping to the system; which is not captured by a simple spring model of the rock.

There also exists frictional losses between the walls of the hole and the drill tube and between the drill buttons and the indentation in the rock, etc.

Furthermore, the indentation of buttons in the rock will resist the torque provided to the drill string by the hydraulic rotation system when the drill buttons are rotated out of the indentation.

Factors that affect the movement of the bit, like friction between the drill button and the rock, will also influence the dynamics of the system.
7. Conclusion.

The developed MDOF model provides the start of the process of increase the understanding of the dynamics of the DTH drilling process. This basic model gives satisfactorily results with various interactions roughly in the same order of magnitude as observed during various measurements. A lot of refinements of the current MDOF model are required to obtain a “good” model of the drilling DTH process, where the influence of other mechanisms like the hydraulic feed mechanism, various source of resistance like the hole wall to tube interaction etc., are to be included. Currently, work is going on to increase the relevance of the simulation model.

The Knowledge gained from the 1D model will be used to make a 3D model that would enable the inclusion of more physics factors like the effects of rotation, etc. Inclusion of 3D rock models that simulate the rock behaviour will also be a key aspect of robust 3D simulations.

REFERENCES


