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Semi-analytical model of the axial movements of an oil-well drillstring in vertical wellbores

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ABSTRACT

A lumped element model for the axial movement of an oil-well drillstring is presented. In this paper, the model is restricted to vertical holes, where damping is due to skin friction from time dependent Newtonian annular Couette-Poiseuille flow. The drillstring is constructed of pipes with different diameters and the diameter of the hole varies as a function of depth. Under these assumptions, the axial movement anywhere in the drillstring is basically a convolution between the axial movement on the top and a semi-analytical function that is derived in this paper. Expressions are given for transfer functions for downhole movements and pressures (surge and swab).

In a vertical drilling situation, the motion is clearly underdamped, even when the hole is tight. The semi-analytical model illuminates various factors that are shown to be important for describing downhole pressure and motion. In particular the effect of added mass, the steady state viscous forces, the Basset viscous forces and the distribution of pipe sizes in the hole. The latter have non-neglectable impacts on where the resonant frequencies are located, how much they are amplified and what happens to the downhole pressure.

Together with statistical power spectra of ocean wave patterns and the response amplitude operators for a floating structure, this model illustrates design concerns related to heave motion and how fast one can run the drillstring into the hole. Moreover, because of the computational simplicity of computing the convolution, the model is well suited for a real-time implementation.

1. Introduction

Operations with floating structures involve taking into account disturbing energy from the ocean waves. An important feature regarding floating structures is to ensure that energy from frequencies in the range of the ocean waves is damped as much as possible. The receiver amplitude operator (RAO) is a transfer function that describes how the floating structure reacts to harmonic waves with different frequencies. There are typically RAOs for heave, sway and surge, which are vertical, lateral and longitudinal movements. Similarly, there are three RAOs for the three rotational motions as well. These are the pitch, the roll and the yaw motions. Moreover, each RAO is dependent on the main angle of the incoming waves [1].

The power spectrum of the heave motions on a certain floating structure is found by multiplying the RAO of the heave by the power spectrum of the ocean waves. Some frequencies are not damped enough to enable safe operations. To account for this, heave compensation is typically installed on all production pipes. It is also installed on the riser, which is the pipe that connects the floating structure with the installation on the seabed. During drilling, heave compensation is typically installed on the top drive, which is the engine that rotates the drillstring. To some degree, the heave motion is therefore

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accounted for during drilling. However in all operations, drillpipes which make up the drillstring, are connected and disconnected regularly. During these connections, the drillstring is attached to the drill floor and no heave compensation is present.

If the heave motions on the rig excite any of the resonant frequencies in the drillstring, the motions downhole can be severely amplified because the motion can be substantially underdamped. After a connection, the axial drillstring movement downhole can be severe and lowering the bit to the bottom can cause damaging bit bouncing. Moreover, these movements cause surge and swab pressures downhole, which can cause hydraulic fracking of the wellbore or the influx of formation fluid. The model in this paper illustrates when one needs to be particularly careful when lowering the bit and under which weather conditions it is safe to operate.

There is a plethora of models for the drillstring and depending on the problem on hand, various physical approximations are made. In the case of vertical holes, an early model is outlined in Ref. [2], where longitudinal and angular vibrations while drilling are described. A more comprehensive model is given in Ref. [3], where a Cosserat model is used. Here, axial, rotational and lateral motions are described while drilling and focus is given to the vibrational states. This is described further [4]. To our knowledge, the effect of heave motions cannot be described directly from these models unless a model for skin friction from annular Couette-Poiseuille flow is added to account for the damping.

A study that focuses on the effect of heave motion on the drilling process is given in Ref. [5]. In that paper the heave motion on a particular semi-submersible rig is simulated by using statistical ocean wave recordings, i. e. the JONSWAP spectrum, multiplied by the RAO of the particular rig. The coupled axial and rotational motion of the drillstring is modeled using a bond graph model, which is described in Ref. [6]. In Ref. [5], the focus is on the coupling between the axial and rotational vibrations, but the model could also be used to describe axial motions of the drillstring, while the drillstring is hanging freely. If the damping term is modeled as in Section 2.1, the model in Ref. [5] could be benchmarked towards the analytical model described in Section 2.

The surge and swab pressures that are a result from the drillstring motions are modeled in various ways. In Ref. [7], the downhole pressure model takes into account temporal effects and assumes Newtonian fluid and that the drillstring is rigid. The rigid drillstring assumption is only valid when the heave motion is well within the first natural frequency of the drillstring. On the one hand, the model in Section 2 is a generalization of [7], since elasticity of the drillstring is taken into account. On the other hand, the model in Section 2 does not take into account the temporal effects due to compressibility, which means that the issues raised in Ref. [7] generalizes this paper.

Another important study in this respect is [8], where the effect of heave motion on a non-rotating drillstring in a curved borehole is investigated. Using a Stribeck friction model, a nonlinear damping model is obtained. Because of the axial slip-stick behavior, larger surge and swab pressures are observed. In the situation where the borehole is curved and the drillstring is not rotating, the downhole motions are not just a convolution of a transfer function with the movement at the top, as suggested in this paper. This is because of the strong nonlinear effects.

Unlike the other studies, the model in this paper is analytical, or at least semi-analytical, which has the benefit of better interpretation. The model generalizes the model in Ref. [9], which analytically can compare with the models in Refs. [10–12]. 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 this paper, we have found that the effect of added mass and Basset forces has a significant effect on the downhole pressure and where the resonant frequencies are. Moreover, the method has the potential of being combined with real-time measurements being used to benchmark more complex methods.

The lumped element model of the drillstring is outlined in Section 2, some important properties of the model are given in Section 3, before the paper is concluded in Section 5.

2. Lumped element model of the drillstring

We consider a vertical drillstring of length L that consists of a variety of pipes, including drillpipes, drill collars and potentially heavyweight drillpipes. For readers who are not familiar with the oil-well drilling process, drill collars are stiff heavy pipes that placed on the bottom of the drillstring to account for the compression forces that are present while drilling with a large weight on the bit. The part of the drillstring that contains the drill collar, the drill bit and other equipments is called the bottom hole assembly (BHA).

This is modeled as a set of n blocks that are connected sequentially by n spring elements, see Fig. 1. Unlike in the figure, the blocks have zero length and the distance between each block is $h = L/n$. The cross-section areas of the blocks are different, which allows for the different pipe dimensions in the drillstring.

The springs are free to rotate with respect to the blocks, meaning that the springs cannot take up angular momentum. The wellbore is vertical and a one-dimensional coordinate system is introduced, where positive z is downwards. 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 $Q(t)$ and the origin of the coordinate system is chosen so that $Q(0) = 0$. Note, that running pipe into the hole will increase $Q(t)$.

The coordinate of each block is denoted by $Q_i(t)$, where t is time. In the unrealistic case where all springs are not in compression and not in tension, the coordinate of $Q_i(t)$ is ih. We define $q_i(t)$ by $Q_i(t) = ih + q_i(t)$. The physical state of the drillstring at any time is therefore uniquely defined by the generalized coordinates $q_i(t)$ and $Q(t)$.