Experimental Studies with Drill String: Effects of Drill Mud

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Summary: In the present work, the effects of drill mud on drilling dynamics are studied. A laboratory scale arrangement consisting of a flexible rotor and a stator is used, and the authors focus on whirling and stick-slip motions of the drill string. The experimental results are provided in the form of time-domain and frequency-domain responses. A reduced-order model of a rotor enclosed within a stator is developed with consideration for non-linear mud film force. This model is used in the simulations. Comparisons are made between experimental and numerical results, and the influence of the drill mud is discussed. This work is one of the first studies carried out on the influence of drill mud on drill-string whirling motions in a laboratory environment.

Introduction

Exploration of fossil fuels and natural gas relies heavily on deep-well drilling systems. In rotary drilling systems, which are commonly used for deep drilling, a rotational drill bit is employed. This bit is an important component of the drilling system. During cutting of the rock surface, this bit undergoes stick-slip and impact dynamics. The drill bit is driven from the surface through an arrangement made up of a slender system of connected pipe-like structures, called the drill string, which helps transfer the energy from the motor to the drill bit [1-3]. To reduce the interactions between the borehole/rock and bottom assembly, drill mud, which flows through the drill string, is pumped through nozzles in the bit. Drilling fluid effects have been studied in prior efforts [e.g., 4], as they can be used to facilitate the drilling process by removal cut material from the hole, cool and lubricate the bit, maintain well bore stability, and help manage the contact between the drill pipes and well bore.

Through downhole and surface monitoring, it is known that a drill string goes through nonlinear motions, including violent torsion oscillations and whirling. Some of these motions are characterized as stick-slip motions (e.g., [5, 6]) as well as large amplitude motions. During operations, a drill string may undergo forward whirling without any contact with the surroundings, forward whirling with contact, or backward whirling with contact. When the radial displacement of the string is large enough, the drill string can come into contact with the outer borehole wall and stick-slip motions could follow. The nature of contact can be influenced by drill-mud properties. Drilling mud formulation and treatment have been the subject of many research efforts, with a focus on rheology. However, the influence of drill mud on whirling dynamics of a drill string has received limited attention in the literature. In one study [7], the drilling mud is assumed as providing a constant viscous damping through drill string. In another study [8], the researchers concluded that stick slip oscillation could be avoided with the selection of an appropriate damping ratio in an active damping system. Jansen [9] and Cull and Tucker [10] considered the effects of mud damping to reduce drill-string vibrations. The damping due to drill mud has been modelled as hydrodynamic drag [11] with nonlinear characteristics. The effect of the drilling fluid and its rheological properties, on stick-slip behaviour still need further attention. The goal of this work is to further the current understanding of the influence of drill mud on whirling dynamics of a drill string.

Experimental studies

In Figure 1, the authors have shown the experimental arrangement. This system, which is representative of a portion of a bottom-hole assembly (BHA), is about a 24:1 scaled down version of a real drilling system. Here, a rigid disk called the rotor is located at one end of a flexible and rotating aluminium structure, the drill string. This combination is confined within a stator. The upper end of the system is connected through a motor shaft to a servomotor, which is used to drive the system at a constant rotation speed. The drill string experiences both bending and torsion motions. To enhance stability of the rotor-stator system, drilling mud is added between the outer shell and rotor disk as shown in Figure 2.

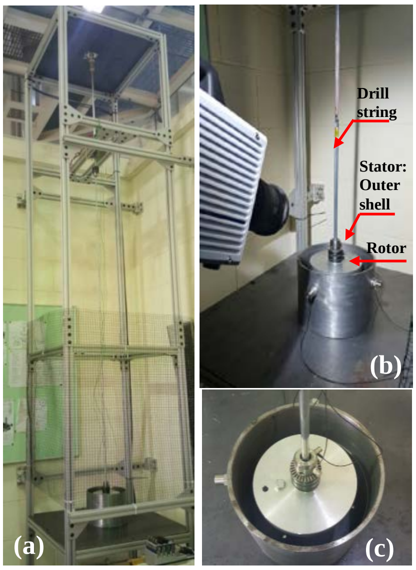

Figure 1. (a, b) Laboratory scale drill-string experimental arrangement at Qatar University used to study drill mud effect. (c) Rotor-stator system.

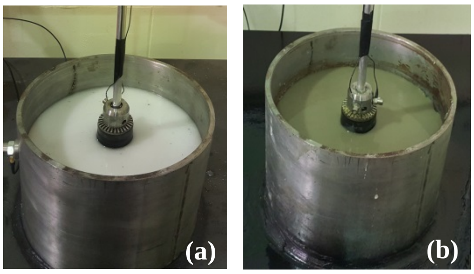

Figure 2. Experimental arrangement with drilling mud: (a) Xanthan Gum water based mud. (b) Bentonite water based mud.

The drill-mud component in a drill-string system are to intended to provide control of density, viscosity, filtration control, PH, lubrication, and shale stabilization, as well as protection from toxic/ corrosive agent. In the experiments, the first tested fluid is the one shown in Figure 2(a). This fluid is water based with Calcium Carbonate ($CaCO_3$) as weighting material, sodium carbonate (Na_2CO_3) as hardness control agent, caustic soda (NaOH) for pH control, starch as filter loss reducer, and Xanthan Gum monomer as viscosifier. The second tested mud, which is shown in 2(b), is a simple mud system called 'base-mud'. This fluid is 6% of bentonite mixed with fresh water. Bentonite non-Newtonian suspensions help in transferring rock cutting to the surface and maintaining stability of the borehole. Among the properties that drilling fluid must possess are appropriate viscosity ϑ and fluid density values ρ. Rheology tests for two fluids considered were carried out and the results obtained are presented in Table 1.

The experiments are carried out for the same ambient conditions, and the response data are collected with accelerometers oriented to pick up lateral motions. Two different drive speeds are used in the experiments.

Table 1. Drill Mud Rheological Properties

Quantities	Parameter	Value	Units
Xanthan Gum water based mud	ϑ_1	27×10^{-3}	Pa·s
	ρ_1	1010	g/L
Bentonite water based mud	ϑ_2	59×10^{-3}	Pa·s
	ρ_2	1633	g/L

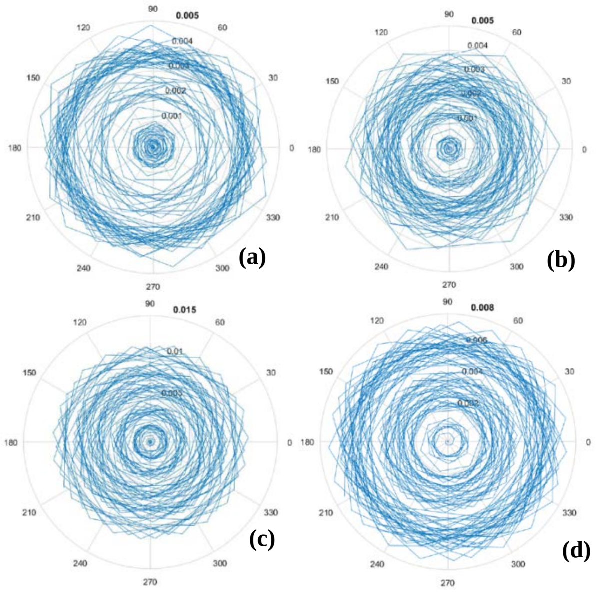

Figure 3. Experimental plot of rotor trajectory with water based mud: (a) response with Xanthan Gum based mud at Ω=80 rpm, (b) response with Xanthan Gum based mud at Ω=110 rpm, (c) response with Bentonite based mud film at Ω=80 rpm, and (d) response with Bentonite based mud at Ω=110 rpm. The maximum radial distance varies from one plot to another.

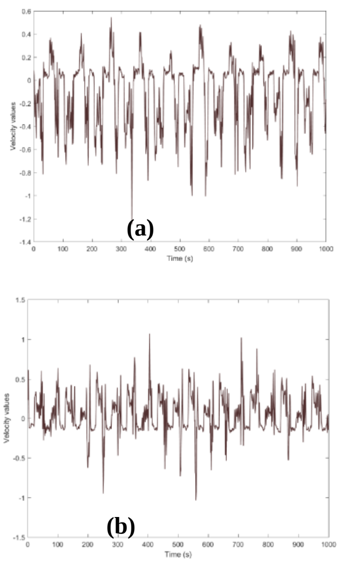

Figure 4. Rotor lateral velocity time histories: (a) Xanthan Gum water based mud. (b) Bentonite water based mud.

In Figures 3(a)-3(d), the authors illustrate the effect of increasing drive speed on the rotor trajectory. The following drive speeds are used: i) Ω = 80 rpm and ii) Ω = 110 rpm. From the polar plots, it is noted that with increasing speed rotation, the rotor spends longer time in the annular space. This observation is in agreement with the results of prior work [12], where the effect of the drilling speed was computationally studied. According to the stick-slip whirl model presented in reference [13], fluid forces acting on the rotor will increase with high rotation speeds, leading to lateral deflections of the drill string and damping of the torsion stick-slip motions. After examining Figures 3 (b) and 3(d), it is mentioned that torsion motion amplitude are reduced when a fluid with higher density and higher viscosity is present between the rotor and the stator.

In Figure 4, the lateral velocity time responses are shown for the two different drill muds, at a drive speed of 80 rpm. The results indicate that with a high-density fluid, there is a decrease in the number of lateral velocity jumps, which are related to stick-slip and impact interactions between the rotor and stator. With the bentonite mud, the corresponding lateral displacements are also attenuated. In Figures 5 and 6, the rotor later displacement frequency responses obtained by sweeping the drive speed in the range of 0 to 110 rpm (1.83 Hz) in forward and reverse directions are shown for cases with Xanthan gum based drill mud and bentonite based drill mud are shown. The displacement levels with the heavier and more viscous bentonite drill mud are lower than that obtained with the other drill mud. This can be attributed to the higher damping levels that the rotor experiences with bentonite drill mud. For both drill mud cases, a

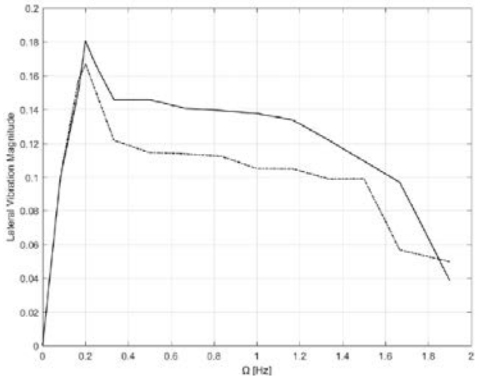

Figure 5. Rotor frequency response obtained in experiments with Xanthan Gum water based mud. The solid line corresponds to a quasi-static sweep of the drive speed in the increasing direction, and the dashed line corresponds to a quasi-static sweep in the decreasing direction.

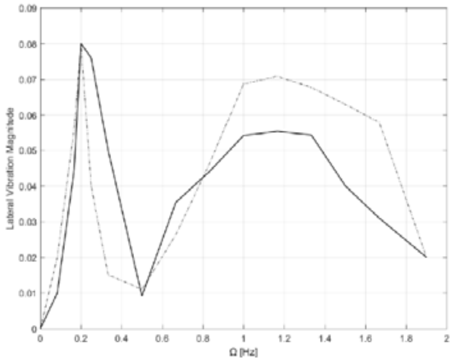

Figure 6. Rotor frequency response obtained in experiments with Bentonite water based mud. The solid line corresponds to a quasi-static sweep of the drive speed in the increasing direction, and the dashed line corresponds to a quasi-static sweep in the decreasing direction.

response peak at 12 rpm (0.2 Hz) is present. This corresponds to one of the system natural frequencies. In the bentonite mud case, an additional response peak is observed at 70 rpm (1.12 Hz).

Model development and computational studies

In Figure 7, a schematic of mud-film rotor-stator system used to develop a model is shown. Equations governing the lateral and torsion displacements of the rotor within the stator are developed.

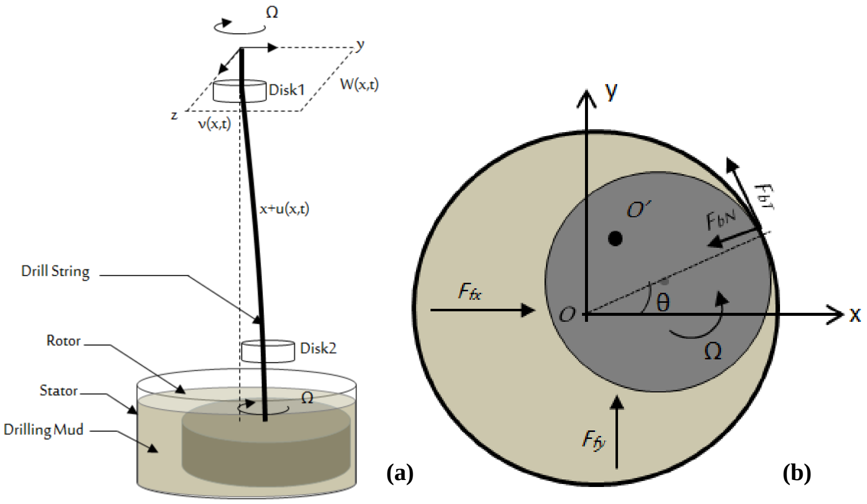

Figure 7. Representative model used for developing a reduced-order system.

The rotor trajectories obtained with the different drill muds and low and high drive speeds are shown in Figure 8. The qualitative nature of these plots agree with those seen in the experiments.

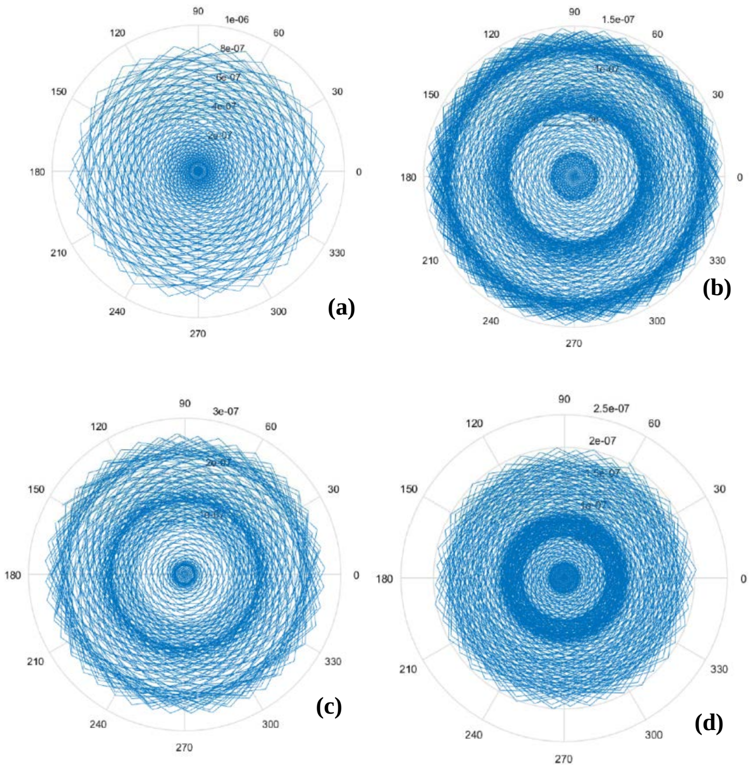

Figure 8. Numerically obtained rotor trajectory with water based muds: (a) Xanthan Gum based mud and low drive speed. (b) Xanthan Gum based mud and high drive speed. (c) Bentonite based mud film and low drive speed. (d) Bentonite based mud and high drive speed.

Concluding remarks

In this work, experiments have been conducted with two different types of the drill mud between a rotor and a stator, with a focus on attenuating stick-slip motions. Water based drill muds were used, one with low density and low viscosity and another with high density and high viscosity. The experiments and numerical studies suggest that with heavier and more viscous drill mud, the response attenuation can be quite pronounced at low drive speeds while the behaviour can be complex at high drive speeds. The drill mud used can be quite influential in extending the range of drive speeds when the rotor is not in contact with the stator. In ongoing studies, the numerical studies are being continued and comparisons are being made with the experimental results.

Acknowledgements

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