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Parametric studies on drill-string motions

Chien-Min Liao [a], Nicholas Vlajic [a], Hamad Karki [b], Balakumar Balachandran [a,*]

[a] Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA
[b] Department of Mechanical Engineering, The Petroleum Institute, Abu Dhabi, United Arab Emirates

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A B S T R A C T

Experimental and numerical investigations are conducted into drill-string motions. The numerical efforts are carried out by using a reduced-order model with attention to stick–slip interactions between a drill string and an outer shell. These efforts are complemented by experimental studies conducted with a unique, laboratory scale model. Qualitative and quantitative changes in the system behavior are studied with respect to the rotation speed and mass imbalance. Comparisons are made between the numerical findings and the corresponding experimental results. In addition, the influence of contact conditions between the drill string and the outer shell on the drill-string dynamics is also examined. The findings of the work suggest that small changes in the system rotation speed can have a significant influence on the nature of drill-string motions and they also provide guidelines for steering the system out of regions of undesirable dynamics and maintaining drill-string motions close to the center of a borehole.

1. Introduction

In mining for petroleum and natural gas resources, boreholes that run many kilometers below the ground are created by using long, slender structures called drill strings, which are a part of a drill-rig system (e.g., see Fig. 1). This drill-rig system consists of a hoisting mechanism, driving system, and drill-mud circulating component. The driving system includes the drill string, bottom-hole assembly and drill bit. The failure of the drill string can shut down the whole drilling process. Structurally, the drill-string assembly, which is housed inside a drill pipe, consists of the drill string and drill collars. Based on the function of the drill collars and drill bit, these two parts together are referred to as the bottom-hole assembly (e.g., [1]).

An extensive number of prior efforts have been devoted to understanding drill-string vibrations, including the following studies [1–12]. Jansen [1] modeled the bottom-hole assembly as an unbalanced rotor supported by two bearings. General descriptions of forward and backward rotations are also recorded within Jansen's work. Following these efforts, Melakhessou et al. [4] developed a four degree-of-freedom reduced-order model to study the bending and torsion motions of the drill string as well as the interactions with the outer shell. Stick–slip and whirl vibrations of a drill string and the influence of the fluid lubrication on it were studied by Leine et al. [3]. They used a two degree-of-freedom model, considered contact conditions in detail, and studied nonlinear instabilities that arise due to discontinuities in the system. This work is illustrative of the complexities of torsion drill-string dynamics including interactions between stick–slip and whirling, and possible instabilities that can be exhibited by such systems. Mihajlović et al. [11] conducted a series of experiments to understand friction-induced vibrations and self-sustained lateral vibrations due to an unbalanced mass in the rotor system. They carried out numerical investigations and studied coupled torsion–lateral vibrations. Further, Mihajlović et al. [12] studied the effect of contact and unbalanced mass on the system dynamics. A study of coupled torsion–bending vibrations with appropriate consideration to stick–slip interactions was carried out recently in the authors' group [13]. Here, building on this recent work, the authors examine the influence of different contact conditions and parameters such as the rotation speed and mass imbalance on the system dynamics.

In this paper, a reduced-order multi-degree-of-freedom model is developed from system energy by means of Lagrange's equations. The model predictions are both qualitatively and quantitatively compared with experimental results by examining system trajectories and diagrams of qualitative changes. It is seen that the model is able to predict the experimentally observed impacting, stick–slip motions, and forward and backward rolling motions. The rest of this paper is organized as follows. Next, the experimental arrangement and results are presented. This is followed by a discussion of the reduced-order model and its features. Subsequently, the parametric studies are discussed and comparisons

* Corresponding author.
E-mail addresses: gimmy@umd.edu (C.-M. Liao), vlajic@umd.edu (N. Vlajic), hkarki@pi.ac.ae (H. Karki), balab@umd.edu (B. Balachandran).

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Nomenclature

Variable	Definition of parameters
D	Outer shell inner diameter
d	Rotor diameter
F_t	Friction force
I_1	Stator moment of inertia
I_2	Rotor moment of inertia
K_p	Stiffness of outer shell
K_r	Stiffness along radial direction
K_t	Stiffness along tangential direction
K_{tor}	Stiffness along torsional direction
m	Mass of rotor
m_b	Unbalanced mass on rotor
R	Radius of rotor
α	Rotation displacement of rotor
θ	Rotation displacement of stator
λ	Contact coefficient
ρ	Lateral displacement of rotor
ρ_0	Initial position of rotor
ϕ	Rotation displacement due to bending

are made between numerical and experimental results. Finally, concluding remarks are collected together and presented.

2. Experimental setup and findings

The experimental arrangement shown in Figs. 2 and 3 is a scaled down version of a drill-string system used in the field in terms of the drill-string diameter, and the scaling ratio is approximately 25:1 ratio [13].

The arrangement represents a section of the drill string between two drill collars. A tunable speed motor is used to drive the system at top, as shown in Fig. 2(b). An encoder is located at the top of the string to measure the rotating speed. A mass representative of an unbalance is attached to the bottom disk, and this unbalance can be thought as arising due to the curvature of a drill string as well as due to other factors. An outer shell made of aluminum is used to simulate the borehole, and to study stick–slip interactions between the drill string and the outer shell. The periphery of the bottom disk as well as the inner side of the outer

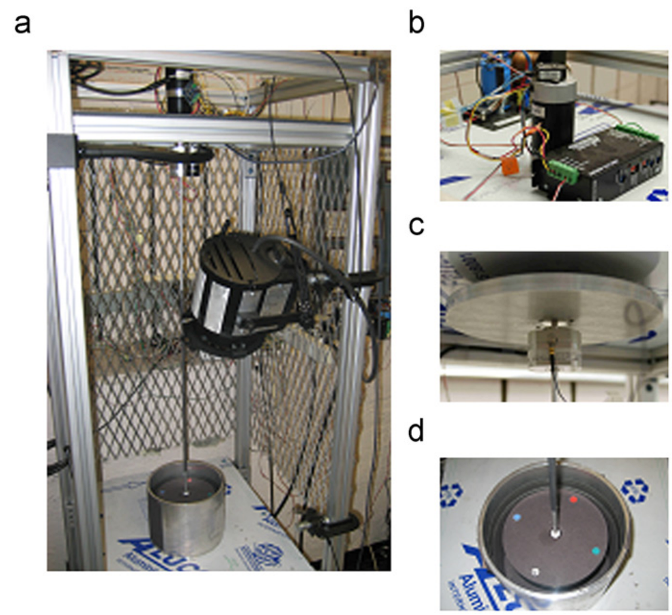

Fig. 2. Experimental arrangement: (a) whole assembly, (b) motor and controller, (c) top disk with encoder, and (d) bottom disk.

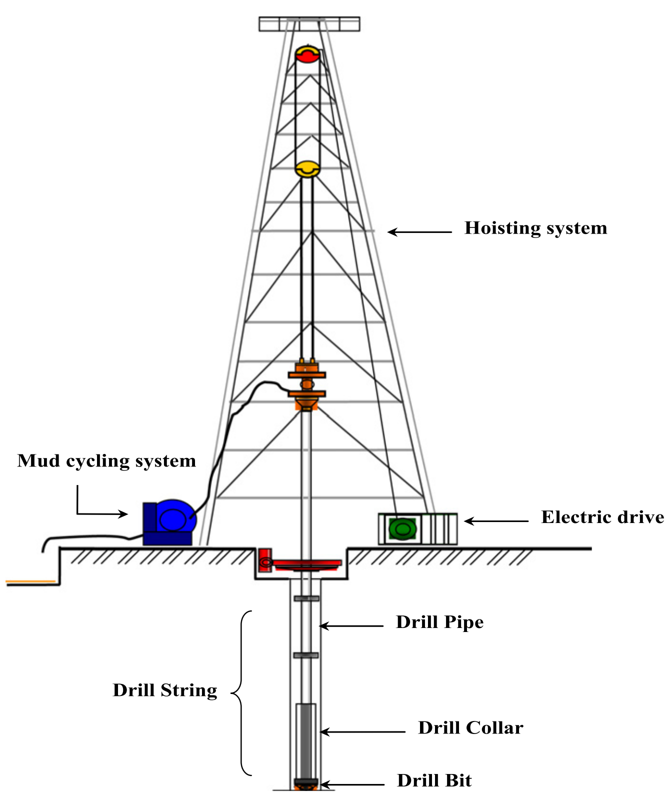

Fig. 1. Illustration of a rotary drill rig.

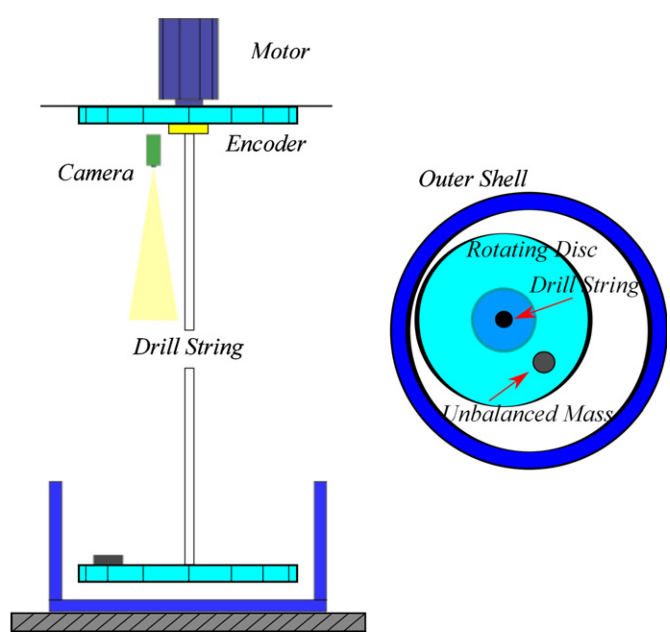

Fig. 3. Side view and top view of the experimental setup, along with the video camera.