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Experimental studies of forward and backward whirls of drill-string

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ABSTRACT

In this work we investigate forward and backward whirls of a drill-string using a novel experimental drilling rig (Wiercigroch, 2010) capable of reproducing major types of drill-string vibration, including stick-slip, bit-bounce and whirling. We focus our attention on whirling motion of the Bottom Hole Assembly (BHA) with a particular attention to the co-existence of forward and backward whirls. We present experimental results, showing for the first time co-existing whirling solutions and characterizing the parameter space in which different whirls can be observed. Those results are then used to calibrate a simple mathematical model, which can be used for further studies of whirling phenomena.

1. Introduction

During a downhole drilling excessive vibration can occur, which in most cases have a negative effect on the drilling process. Such vibration may lead to an accelerated wear and a premature damage of the expensive drilling equipment. Often different dynamic effects such as bit-bounce, stick–slip, forward and backward whirls may appear for the same drill-string arrangement. In this paper we focus on the whirling of the BHA inside the borehole, which is still not well understood and can lead to catastrophic failures of drill-strings. As depicted in Fig. 1, there are two types of whirling motion: forward and backward whirls, for which the direction of rotation of the BHA coincides (forward) or differs (backward) with the direction of whirling motion. From those two, the backward whirl is a bigger threat to the drilling process, as it induces high frequency vibration. Besides, lateral vibration can lead a drill-string to bend and as a consequence it can compromise the borehole stability [2,3].

The whirling phenomena have attracted a considerable attention throughout the years including both numerical and experimental studies. Theoretically, most of the efforts have been on utilizing low dimensional models, based on a rotor concept, to mimic different types of whirling motion. A good summary of modelling efforts of different vibration modes is given in Ghasemloonia et al. [4]. In many cases this includes coupling of the lateral degrees-of-freedom (DOFs) with the torsional ones. Liao et al. [5] introduced four and five DOFs reduced models, coupling torsional and lateral dynamics, which proved to be in a good agreement with experimental results. The main solution of mitigating dangerous stick-slip oscillations is

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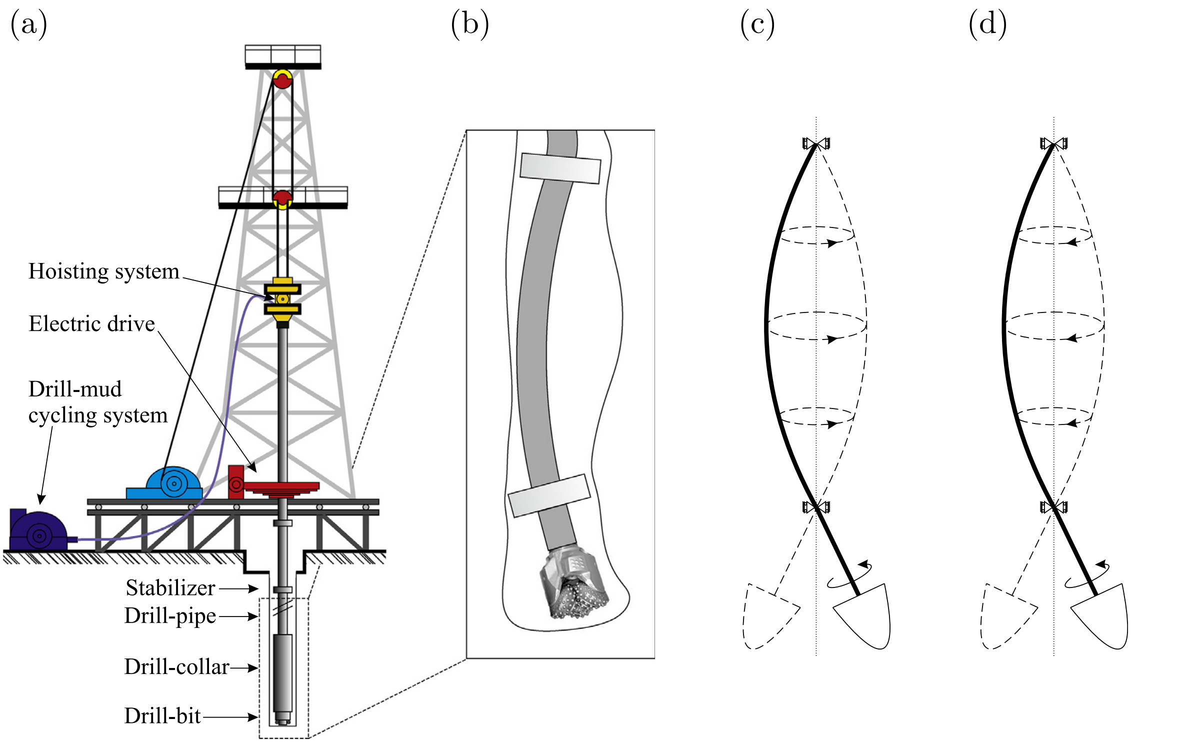

Fig. 1. (a) A schematic showing a typical configuration of a drilling rig with most important components; (b) BHA section; (c) & (d) schematics of BHA whirling motion, forward and backward, respectively.

increasing the drill-string rotary speed, which often results in increased both lateral and axial vibration, whirling, impacts between a drill-string and a borehole, as well as parametric instabilities and bit-bounce [6].

One of the major reasons for whirling phenomenon is the imbalance (for example when the centre of gravity does not coincide with the centre of rotation), that results in its bowing around the borehole [5]. This results in an enlargement of the borehole and may lead to catastrophic failures in the system. In terms of modelling, the whirling has been analysed using unbalanced rotor systems [5,7–9], which represents a simplification of the complex phenomena encountered in downhole drilling problems. It has been broadly investigated in the past using different approaches, which include Jeffcot rotor models (e.g. [7,10]) as well as Finite Element models (e.g. [11,12]). An interesting model has been introduced in [13], where authors proposed a digital filters based model of the drill-string, that takes into account nonlinear characteristics of drill-bit cutting interface and which is able to mimic both stick-slip as well as forward/backward whirls. The asymmetry of the shaft is one of the main reasons for whirling phenomenon [14–16]. However, it has been reported in [17] that whirling can be also affected by the drill-bit rock interactions as well as friction between the BHA and the borehole [18].

There have been many attempts to investigate drill-string dynamics experimentally on various rigs having different capabilities. Warren [19] described a large scale experimental rig, capable of operating under conditions comparable to those observed in the field, whereas Hanson [20] reported a study of whirling tendencies of polycrystalline diamond compact (PDC) drill-bits. Another example of a large scale rig has been described by Halsey et al. [21], where a study of torsional vibration of the drill-string in a nearly vertical, 1000 m deep borehole has been analysed. Due to the limited resources and space restrictions, the rigs developed in the academic institutions have been much smaller in size. In most of them, a drill-string is a slender steel structure, driven by an electric motor from the top, whereas the BHAs are represented as cylinders. Those rigs do not use real drill-bits but simulate the drill-bit rock interactions through different shakers and brakes. Examples of such drilling rigs can be found in [22–24,5], which is contrast to the work by Hoffmann [25], where actual rock samples were drilled. In [26] the authors describe a newly built scaled rig for analysing drill-string vibration, which comprises of a rotating shaft between two stabilizers and is capable of replicating lateral vibration.

The main purpose of the present work is the experimental study of whirling phenomenon, in order to gain some further insight and to develop the calibrated mathematical models capable of accurately predicting the whirling dynamical behaviour. The study is supported by a brief analysis with a simple model, that allows to expand the current understanding of the conditions, that trigger forward and (or) backward whirling motion. Ultimately, this work should contribute to development of simple and easily applicable methods to effectively control dynamics of the BHA dynamics.

The structure of this paper is as follows. In Section 2, we describe in details the experimental rig used to study whirling phenomenon, as well as specify conditions of the experiment. As a next step, Section 3 presents an experimental procedure