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Unveiling complexity of drill–string vibrations: Experiments and modelling

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ABSTRACT

We investigate complex drill–string dynamics on a novel experimental rig [1], capable of reproducing all major types of drill–string vibrations. One of the most important features of this versatile experimental rig is the fact that commercial drill-bits and rock-samples are used. The rig allows for different configurations, which enables the experimental study of various phenomena, such as stick–slip oscillations, whirling, drill-bit bounce and helical buckling of the drill–string. Special attention is given to the estimation of the physical parameters of the flexible shaft, which is the element used to mimic the characteristics of the drill–string and plays a crucial role in the creation of undesired vibrations. Furthermore, a low-dimensional model of the drilling assembly based on a torsional pendulum is developed and calibrated by means of the experimental measurements. In addition, a detail high-dimensional model of the drilling rig is developed using a Finite Elements Analysis approach. The experimental and numerical results demonstrate the predictive capabilities of our mathematical models, in particular when stick–slip oscillations occur.

1. Introduction

A drill–string is an important component of the drilling assembly to create a borehole used mostly for extraction of oil and gas. It exhibits a highly complex dynamical behaviour, which was first discovered when MWD (Measurement While Drilling) tools were introduced to ensure more accurate steering and better drilling efficiency [2]. As can be seen from a typical drilling rig schematically shown in Fig. 1, the rotary motion applied at the surface is transferred to the drill–bit via the drill–string [3], comprised of drill–pipes connected to each other by threaded joints. Apart from providing the rotary motion of the drill–bit, the drill–string transfers necessary axial force, known as Weight On Bit (WOB), in order to facilitate the deep hole drilling process. Drill–strings can reach lengths of several kilometers, which make them very slender structures [4]. A drill–string is mainly built from drill–pipes, which are normally run in tension to avoid helical buckling which can accelerate fatigue resulting consequently in a catastrophic damage. The end section of the drill–string is a Bottom-Hole Assembly (BHA), which is responsible for controlling the rate of penetration, the hole inclination and direction. The BHA is composed of drill–collars working in compression to provide the necessary WOB. It is comprised of heavy drill–pipes, stabilizers, MWD tools and "shock subs" that absorbs vibrations between the drill–bit and the drill–collars.

The dynamical behaviour of drill–strings is very complex, as many dynamic phenomena are present, such as vibrations, bending and twisting quasi-static motion, together with the bit–rock and the drill–string–borehole interactions [3]. As an interplay between these phenomena introduces additional complexity to the system dynamics, it is of utmost importance to fully understand their origins as in most cases they affect significantly the drilling process [6]. Different vibration modes, such as torsional, lateral and axial vibrations influence the dynamics of a drill–string, and their occurrence, especially stick–slip (torsional) vibrations [7–9], lead to a reduction of Rate Of Penetration (ROP). They may cause catastrophic failures and at least wear to expensive components of the drill–string [10–13].

Experimental and numerical study of drill–string dynamics attracted considerable attention for several decades. There are two basic approaches in modelling dynamical phenomena in drill–strings: (i) low-dimensional dynamical models focussing on

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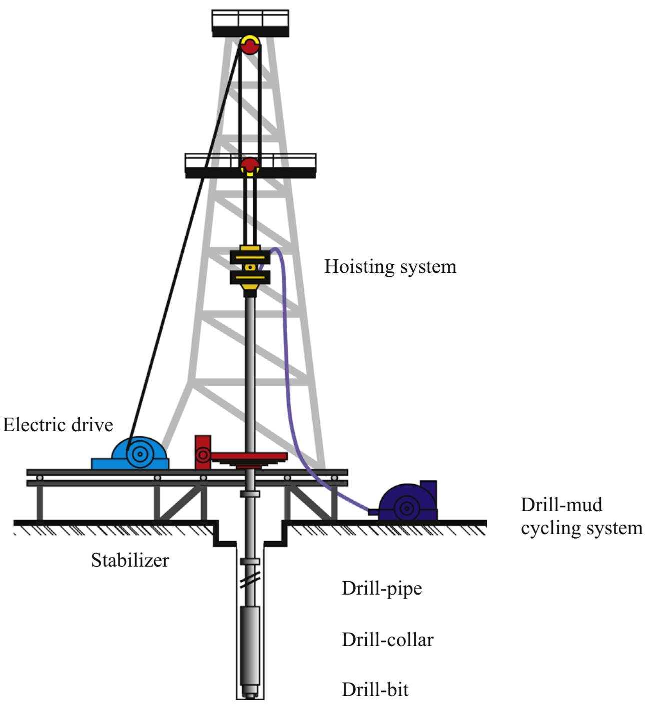

Fig. 1. A schematics of a typical drilling rig as used by the drilling industry, showing most important components: drill–bit, drill–collars, drill–pipes, stabilizers, drill-mud circulating system, hoisting system used for controlling WOB and an electric drive providing rotary motion to drill–string. Adopted from [5].

few dominant modes and (ii) full scale continuous models analysed in majority cases by Finite Element (FE) based methods. One of the most popular approaches to investigate drill–string systems is based on torsional pendulum models, which has been studied by many researchers including Yigit and Christoforou [14,15], Jansen and van den Steen [16] and Richard et al. [17]. In their work, the emphasis was put on the nonlinear relationships of bit–rock interactions and a coupling between axial and torsional modes of vibrations. One of the major limitations of low-dimensional models based on torsional pendulum, is their inability to mimic two important characteristics: (i) the fact that a drill–string length increases during the process and (ii) the vibrations along drill–string composed of connected drill–pipes and drill–collars. To address this issue, a multi-dimensional lumped-parameter model, that overcomes these disadvantages, has been proposed by Navarro López, Cortés and Balachandran [18–21].

Another important area in drill–string dynamics is modelling of the bit–rock interactions. The simplest approach considers dry friction [22] or models combining dry friction with exponential-decaying laws [16,18,5]. More advanced formulations decompose the Torque On Bit (TOB) and WOB into cutting and frictional force components, which are functions of the Depth Of Cut (DOC) and a velocity independent friction [23,24], contrary the studies, where velocity-weakening effects are taken into account [25–27]. Based on the chatter modelling in metal machining [28], Richard et al. [17] proposed the time history dependent nature of the bit–rock interactions. Due to the coupling between axial and torsional motion, the so-called regenerative effect takes place, which is produced by the interplay between cutting and contact forces. It accounts for the dependence of the thickness of material removed by a cutter on the position of the cutter at the previous revolution of the workpiece, and is identified as the cause of self-excited axial vibrations [29]. To combat this effect a feedback can be introduced into the system, as the current force which depends on the instantaneous DOC, is influenced by the axial position of the tool at the previous bit revolution. This type of modelling requires the use of Delay Differential Equations (DDEs) [30].

As mentioned earlier, modelling techniques based on Finite Element Methods (FEM) have been also considered to study drill–string vibrations. One of the first attempts to use the FEM in drill–string analysis has been performed by Millheim et al. [31], who used a custom made code MARC-CDC to model the BHA dynamics. Many FE analyses have focussed on modal characteristics of BHA (see e.g. [32]), whereas Axisa and Antunes [33] presented a dynamic modelling of the whole drill–string using FEM. Although both flexural and torsional motions were included, the coupling between them was neglected. Most of the studies concerning the whole drill–string are similar in this respect, differing mainly in the choice of beam element and various ways of describing TOB characteristics.

Sampaio et al. [34] proposed to study the coupling between axial and torsional vibrations of a drill–string by using a geometrically nonlinear model. The geometrical nonlinearities, whose importance in the context of dynamics of structures have been investigated by Trindade and Sampaio [35] and Banerjee and Dickens [36], where the beam's stiffening was introduced. Al-Naser and Khulief [37] proposed a Lagrangian based FE model to describe the dynamics of the drill–string that includes drill–pipes and drill–collars. It takes into account gyroscopic effects, axial stiffening, inertia coupling, coupling between torsional and bending vibrations and the effect of the gravitational force. The model has advantages over the works by Dunayevski et al. [38], which neglects gyroscopic effects and axial stiffening. Berlioz et al. [39], who despite including both gyroscopic and fluidelastic effects, do not take into account the axial stiffening. The proposed model in [37] follows the idea of Tucker and Wang [40] to describe the drilling assembly as an integrated system. Another FE model used to study drill–string dynamics has been analyzed by Ritto et al. [41], where uncertainties in the bit–rock interaction are described by means of a non-parametric probabilistic function. This follows the approach proposed in Spanos et al. [42] and Kotsonis and Spanos [43] for the analysis of stochasticity in drill–string dynamics. Germay et al. [29] extended the approach proposed in [17] by treating the drill–string as a continuum and utilizing FEM (using Euler–Bernoulli beam model) to study self-excited vibrations. Applying this approach allows us to observe multiple axial and torsional natural modes of vibration, in contrast to torsional pendulum applied earlier [17]. Jafari et al. [44] studied the effects of drilling mud flow rate, drill–string weight, WOB and angular velocity on the stability of the drill–string. In that investigation, they observed that for an increased drilling mud flow rate and angular velocity, the critical height of neutral point decreases as do the natural frequencies for the same conditions. It was shown that a drilling mud can act as a damper, thus decreasing amplitude of vibration. On the other hand, Qian et al. [45] considered buckling and flutter of a drill–string under the influence of drilling mud flow. In all these investigations, the FE models have been constructed under the assumption of a perfectly vertical bore-hole. Recently, Hu et al. [46] proposed a new FE model to describe the dynamics of a drill–string in a curved borehole. The approach involves the use of a spatially curved beam element whose length is assumed to have a small value in order to ensure accuracy and thus increasing the computational effort [47]. On the other hand, Hakimi and Moradi [48] proposed to apply the differential quadrature method, introduced by Bellman et al. [49] to study vibrations of a drill–string operating in a near vertical bore-hole. It is applied to the system of nonlinear equations of motion and their corresponding boundary and contact equations, what requires solution using the Newton–Raphson method. The proposed approach is validated by comparing the calculated lateral natural frequencies with the results obtained by Burgess et al. [32], who