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EXPERIMENTS AND MODELLING OF COUPLED AXIAL-TORSIONAL DYNAMICS IN A DRILL-STRING

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Abstract. *We investigate the coupled axial-torsional dynamics of a drill-string on a novel experimental drilling rig incorporating the most recent additions to its configuration. This includes a micro drill-bit and a laser displacement sensor allowing to apply realistic drilling conditions and for an accurate measurement Rate Of Penetration (ROP), respectively. A programme of experimental studies aiming to investigate drill-bit and rock interactions was conducted. Furthermore, we observed a spectrum of various phenomena including slick-slip, helical bucking and others. Next, a dynamical model of the drill-string rig was developed and calibrated using the experimental results. Once the model was validated, it can be used to implemented numerical analysis, which combined with the good agreement between experimental and numerical results reported in this paper allow us to deepen understanding of complexity of drill-string dynamics.*

Keywords: *Drill-string dynamics, Drill-bit rock interactions, Nonlinear mechanisms, Experimental studies, Mathematical modelling*

1. INTRODUCTION

In drilling engineering, drill-string possesses complex dynamical behaviour because of strongly nonlinear factors, mainly its own slenderness, drill-bit rock and drill-string wellbore interactions (Spanos *et al.* (2003)), which often excite undesired vibrations in three main modes: torsional, lateral and axial (Christoforou and Yigit (2003)). Their occurrence, especially the stick-slip vibration in torsional direction (Wiercigroch (1994); Dankowicz and Nordmark (2000)), will inevitably accelerate drill-string failure, thereby increasing drilling cost by at least 10% (Jardine *et al.* (1994)).It is exactly that factor which attracts more and more interest in modeling and experimental studies of drill-string dynamics (Tang *et al.* (2019); Li *et al.* (2017); Saldivar *et al.* (2016)). However, experimental study of coupled axial-torsional vibration in drill-string has rarely been reported, and until now there exists no robust model that can exactly predict its coupled axial-torsional dynamics. Therefore, this paper is aimed at developing and calibrating the mathematical model of coupled axial-torsional vibration of drill-string based on the experimental results. This study should help us to better understand complex and nonlinear drill-string dynamics, which will lay a foundation for mitigating and suppressing drill-string vibrations robustly in the future.

The structure of this paper is as follows. In Section 2, we describe briefly the experimental rig used to investigate drill-string dynamics, as well as its most recent configuration upgrades. As a next step, Section 3 presents the experimental studies of drill-string dynamics. Subsequently in Section 4, we introduce and calibrate a drill-string dynamical model, that allows to obtain good qualitative and quantitative agreement with experiments. Finally, Conclusions and future work are discussed in Section 5.

2. EXPERIMENTAL RIG TO STUDY DRILL-STRING DYNAMICS

In this section we describe briefly the versatile experimental rig developed at the Centre for Applied Dynamics Research at University of Aberdeen, which will be used to investigate the bit-rock interaction and coupled axial-torsional vibration of a drill-string. Its main structures have been discussed in authors‘ doctoral dissertations (Kapitaniak (2015); Vaziri Hamaneh (2015)). As can be seen from Fig. 1(a), the drilling system is driven by a top motor of which maximum rotational velocity can be as high as 1370 revolutions per minute (rpm). Rotational velocity generated by the top motor is delivered to the Bottom Hole Assembly (BHA) using either a rigid or a flexible shaft. In our experiments, the BHA is held in place inside a loose bearing with a radial clearance of 0.47 mm to restrict its lateral motions. Steel disks are added on top of the BHA to provide a required Weight On Bit (WOB), while the drill-bit is connected at the bottom of the BHA though a bit holder. In the experimental rig, the top and bottom encoders are used to measure the rotational velocities of the motor and the BHA, respectively. The Torque On Bit (TOB) and WOB arising from drill-bit rock interaction are measured by a load cell fixed below the rock-holder plate. The electrical signals generated by all sensors are collected by a purposely built LabView system for visualizing and saving the results.

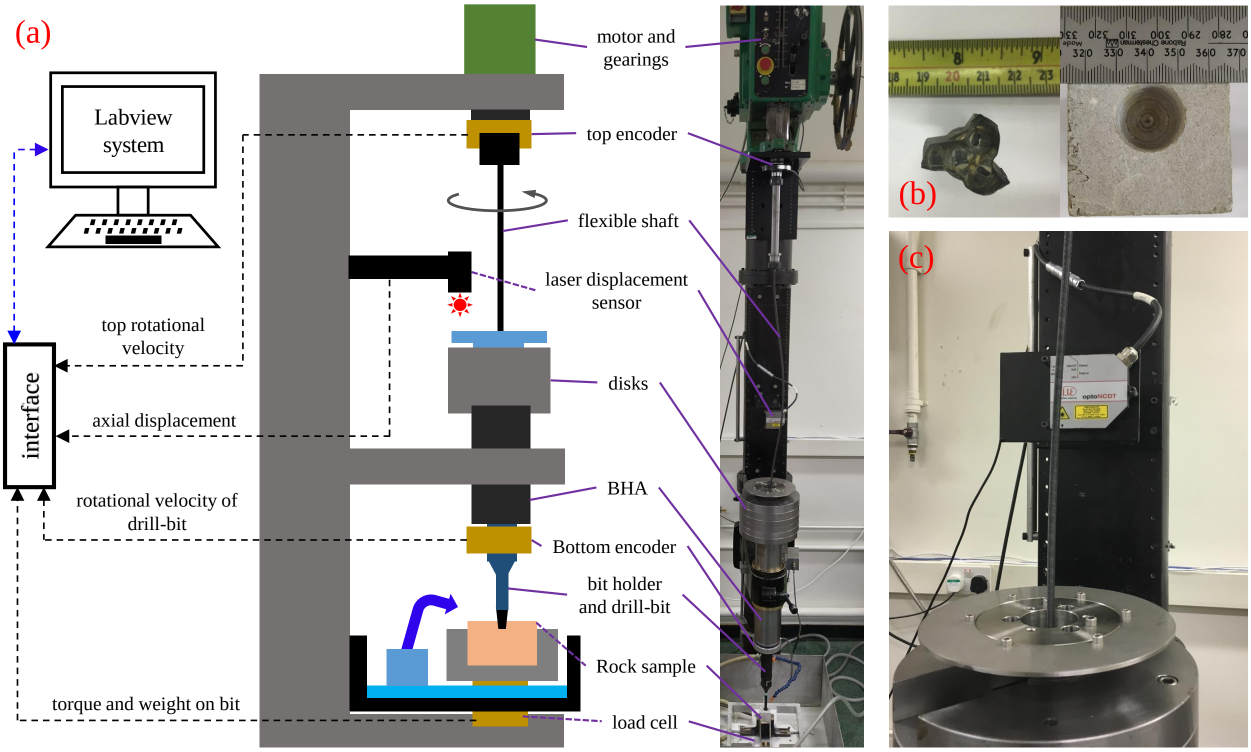

Figure 1. (a) A schematic diagram (left) and photograph (right) of the experimental drilling rig showing its major components, (b) micro drill-bit and rock sample used in our current experiments, and (c) laser displacement sensor used for measuring vertical progression of the BHA.

Note, that two new innovative elements are also introduced in our experiments. First one is a micro drill-bit with diameter of 22 mm incorporated into the drill-string, which allows for comprehensive insight into both cutting and frictional components of drill-bit rock interaction, as shown in Fig. 1(b). The second upgrade of the experimental rig is that the original linear variable differential transformer (LVDT) is replaced by a laser displacement sensor allowing for significant improvements in measurement accuracy of axial displacement of the BHA, equivalent to ROP, as depicted in Fig 1(c). Therefore, our current work differs from authors‘ previous studies (Kapitaniak (2015); Vaziri Hamaneh (2015); Kapitaniak *et al.* (2015, 2018); Vaziri *et al.* (2018)), in which a standard-sized (3 7/8" OD) commercial drill-bit was used, resulting in negligible Depth Of Cut (DOC) due to limited WOB applied, that itself allowed us to use a simpler dry friction model for bit-rock interaction representation.

3. EXPERIMENTAL STUDIES OF DRILL-STRING DYNAMICS

3.1 Experimental study of drill-bit rock interaction

In order to establish a mathematical model for coupled axial-torsional vibration of a drill-string, and calibrate it with experimental data, it is essential to develop a precise drill-bit rock interaction model. With that in mind, we perform experimental studies of drill-bit rock interaction combined with identification of key mechanical parameters required for model calibration. In these experiments, the rigid shaft is employed to connect the top motor and the BHA, ensuring a constant rotational velocity of the drill-bit. We increase the driving rotational velocity of the top motor in four steps from 28.03 to 44.9 rpm, and record the average values of ROP, DOC, TOB and WOB for each step, as shown in Fig. 2. The ROP increases as the driving rotational velocity increases. In contrast, the higher the rotational velocity is, the lower the DOC observed. Interestingly, both TOB and WOB follow similar trend as the DOC. These experimental results are intended to identify the key parameters in drill-bit rock interaction model.

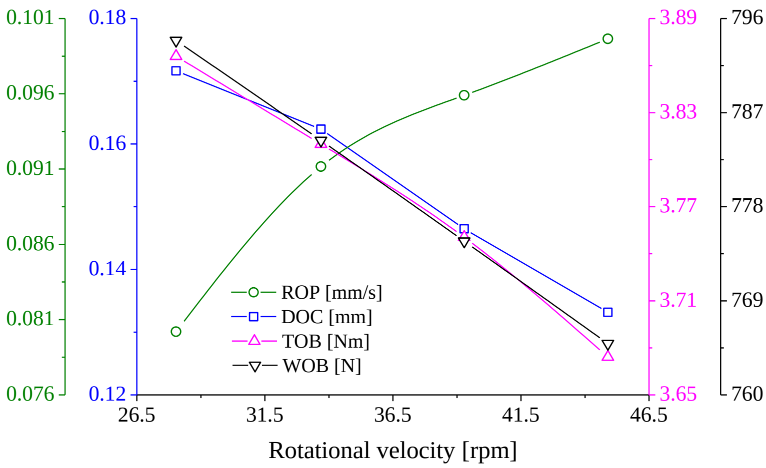

Figure 2. Experimental results of average drill-bit responses under different rotational velocities, where the green, blue, red and black lines represent the ROP, DOC, TOB and WOB, respectively.

3.2 Experiments of coupled axial-torsional vibration in drill-string

In order to observe drill-string vibration, the configuration of the experimental rig needs to be appropriately adjusted in comparison with drill-bit rock interaction experimental setup, which involves selection of a flexible shaft to replicate the dynamical behaviour of a drill-string. In current experiments, a flexible shaft with diameter of 7mm and length of 1m has been employed to connect the top motor and the BHA. For a fixed set of system parameters (drill-bit, rock, flexible shaft and a fixed number of steel disks), the experiments are run at a constant driving rotational velocity and the corresponding dynamical responses of the BHA are recorded. In Fig. 3, we present an example family of time histories of rotational velocity, axial displacement of the BHA, TOB and WOB, where the drill-string system is driven by the top motor with three different rotational velocities, which can be assumed as constant (marked as the red lines). Due to the low stiffness of the flexible shaft, the rotational velocity of the BHA fluctuates over time with a significant amplitude.

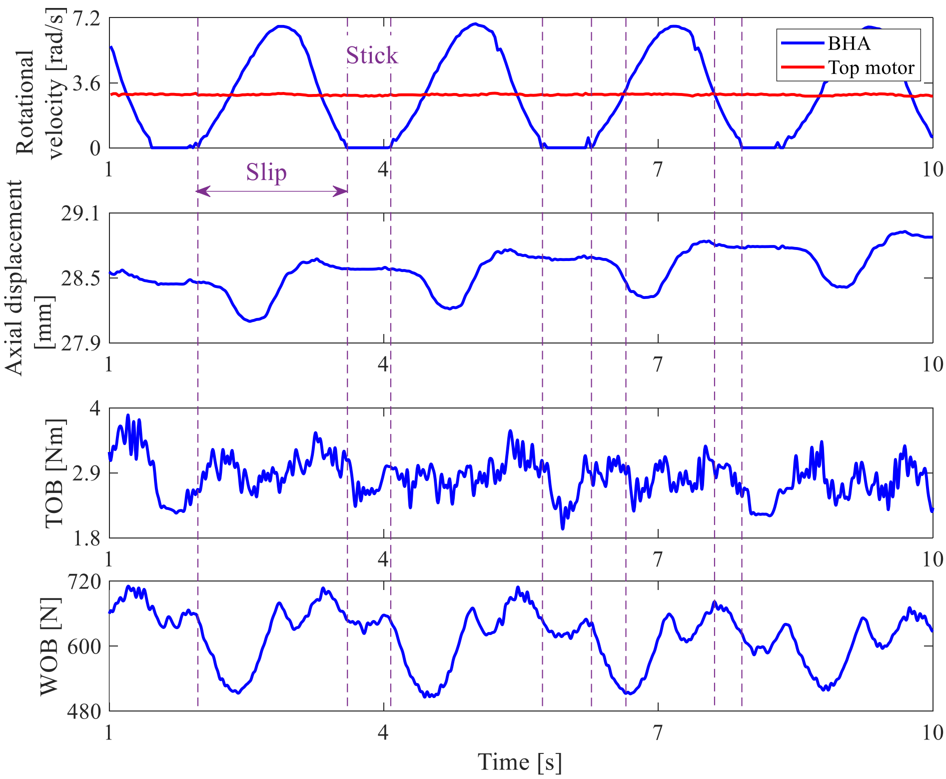

Figure 3. Recorded experimental time histories, including rotational velocity and axial displacement of the BHA, torque and weight acting on the drill-bit (TOB and WOB), for configuration with a flexible shaft under driving rotational velocity of 2.935 rad/s.

Interestingly, the drill-bit may lose contact with the rock due to twisting of the flexible shaft, which manifests itself as a quick, local decrease of the axial displacement. As a result, we observe obvious corresponding amplitude variation in both TOB and WOB, around their average values. Moreover, we present example responses for which the experimental drill-string exhibits typical stick-slip behaviour. During the stick mode the BHA is stationary, resulting in the rotational velocity of 0 and constant axial displacement. Examining closely the time histories, it can be observed that exactly on the onset of stick phase a clear sudden decrease of TOB is visible, indicating reaching a static torque. In the stick phase, the WOB remains almost constant and the TOB increases due to the accumulation of strain energy in the flexible shaft. Once the energy stored in the flexible shaft is enough to overcome the resistance faced by the drill-bit, the BHA immediately changes back to the slip mode. Subsequently, the rotational velocity of the BHA is increasing and achieves the driving rotational velocity indicating that the flexible shaft starts to lose strain energy. Therefore, the axial displacement of the BHA and WOB achieves their local minimum values at this point, and then increases to their local maximums when the rotational velocity of the BHA reaches the driving rotational velocity again, and finally decrease gradually until the system enters a new stick phase. In the total slip phase, the TOB always oscillates.

4. MODEL OF COUPLED AXIAL-TORSIONAL DRILL-STRING DYNAMICS

In order to fully understand the mechanism of coupled axial-torsional vibration, we introduce a mathematical model of the experimental drill-string system in this section, and its robustness is checked carefully by the experimental results. Once the model is validated, we focus our attention on the numerical analysis of its nonlinear mechanisms.

4.1 Equations of motion

The simplified physical model is shown in Fig. 4, where the top part represents a massless rotary table, and its axial motion is restricted completely and rotational motion is described by ϕ_t. An elastic shaft with rotational stiffness k_t and damping c_t connects the rotary table with the BHA, which has a mass m_b and a moment of inertia J_b. Meanwhile, the axial and rotational motions of the BHA are described by variables Z_b and ϕ_b, respectively. Based on these, the governing equations of motion for the experimental drill-string system with axial and torsional dynamics can be written as Eq. (5), in which W_0 represents the equivalent axial load acting on the BHA.

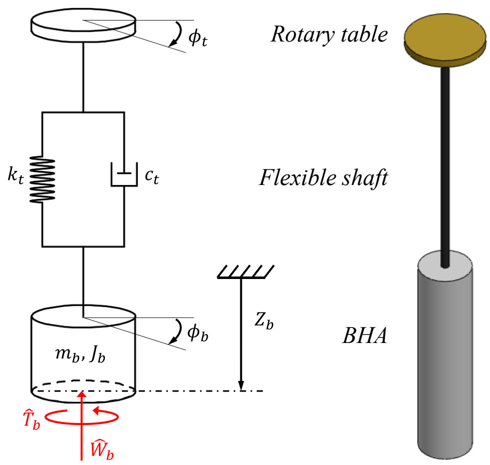

Figure 4. Left panel depicts a lump mass model with two DOF used to capture the axial and torsional dynamics of the drilling system, and right panel is its schematic showing main components: rotary table, flexible shaft and BHA.

$$\begin{aligned} &J_b\ddot{\phi}_b(t) + c_t\left(\dot{\phi}_b(t) - \dot{\phi}_t(t)\right) + k_t\left(\phi_b(t) - \phi_t(t)\right) = -\hat{T}_b, \\ &m_b\ddot{Z}_b(t) = W_0 - \hat{W}_b, \end{aligned} \tag{1}$$

where $\hat{W}_b$ and $\hat{T}_b$ represent respectively the WOB and TOB with considering the various motion regimes of the BHA, including slip-stick and drill-bit bounce, and these two parameters can be determined from the experiments of drill-bit/rock interaction listed in Section 3.1.

4.2 Experimental verification of the model

In this section, an experimental verification of the established dynamical model is carried out. It should be mentioned that the main purpose of this work is to develop a robust model to unveil the complexities and nonlinearities observed in drill-string dynamics. However, in order to grasp their complex interactions gradually, only the axial and torsional motions of drill-string are taken into account in this work, neither its lateral motions nor twisting. Firstly, we consider a torsional response of the BHA for $W_0 = 562$ N, whose experimental time history and phase portrait are shown in Fig. 5(a1), where the driving rotational velocity is $\dot{\phi}_t = 2.932$ rad/s, while the BHA experiences a typical stick-slip vibration. In order to calibrate the dynamical model, the operational and physical parameters in Eq. (1) are kept consistent with the experimental setup, which means that $J_b = 0.255$ kgm^2, $m_b = 73$ kg, $k_t = 2.292$ Nm/rad and $c_t = 0.005$ Nms/rad. For drill-bit rock interaction, we apply the model established in Section 4.1, in which the key parameters can be determined according to the experimental results. The torsional responses from the experiment and the dynamical model are in good agreement, as shown in Figs. 5(a1)-(a2).

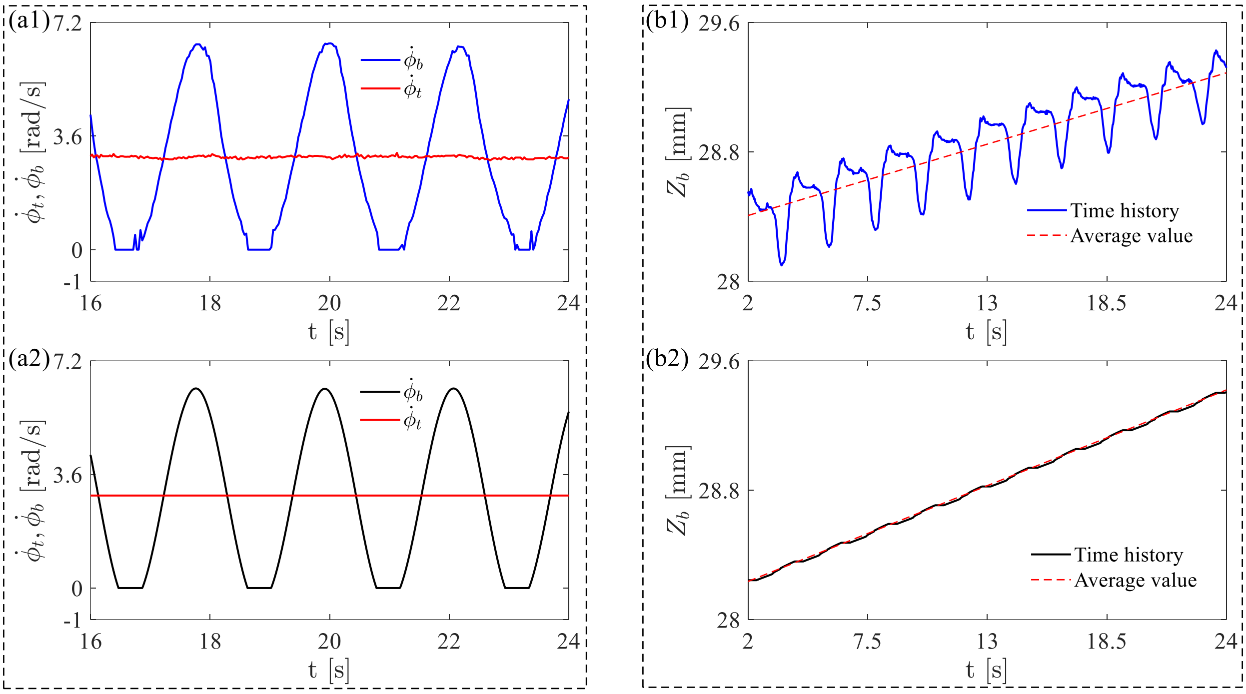

Figure 5. Time histories of (a1)-(a2) stick-slip vibrations and (b1)-(b2) axial displacements for $W_0 = 562$ N and $\dot{\phi}_t = 2.932$ rad/s. (a1) and (b1) are obtained from experimental studies, (a2) and (b2) are obtained from dynamical model.

Following the calibration of the torsional DOF, we proceed to the calibration of the axial motion of the BHA. Let's consider the axial displacement of the BHA for $W_0 = 562$ N, which experimental time history is shown in Fig. 5(b1). The BHA visibly experiences upward motion in the axial direction due to twisting of the flexible shaft, which reduces the equivalent axial load produced by the BHA. In the dynamical model, twisting of the flexible shaft is neglected, so that this upward motion cannot be reproduced. However, we set W_0 in the dynamical model to be equal to the average WOB from the particular experiment, ensuring that the average axial displacements are in excellent agreement between the numerical and experimental results, as shown in Figs. 5(b1)-(b2). By comprehensively comparing two panels depicted in Fig. 5, the good qualitative and quantitative agreement between numerical calculation and experimental results indicate the robustness of the proposed dynamical model, which in turn can be used to predict the coupled axial-torsional dynamical behaviour of the drill-string in certain configuration. Moreover, this robust model allows to unveil the complexities and nonlinearities of drill-string dynamics by numerical analysis method.

5. Conclusions and future work

In this paper, we investigate coupled axial-torsional dynamics of a drill-string on a novel experimental drilling rig developed at the University of Aberdeen, observing a spectrum of various phenomena including slick-slip, helical buckling, regenerative traces in the borehole and others. In view of the positive experimental results and careful parameter identification, a robust mathematical model has been developed to simulate the coupled axial-torsional dynamics of the drill-string more accurately. All of the above can serve as preliminary preparations for developing effective methods to mitigate drill-string vibrations. Furthermore, by using the new beam element developed by authors Kapitaniak *et al.* (2020), a more detailed experimental and numerical studies that take into account twisting of the drill-string will follow, to extend the application range of the developed model.

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