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Modelling of high frequency vibro-impact drilling

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ABSTRACT

Modelling of the vibro-impact drilling system is undertaken in this study, and the results of the numerical analysis and comparison between two selected models are presented. The first one is a newly developed model of an existing experimental rig (three masses model) and the second one is a simplified low dimensional model (Pavlovskaia et al., 2001 [22]) created to describe the dynamic interaction between the drill-bit and the drilled formation. The optimal loading parameters are identified in this work based on the analysis of the system responses, and the influence of the additional degrees-of-freedom on the loading optimisation strategy is investigated. Three main control parameters are considered, and they are the applied static force, and the amplitude and the frequency of the applied dynamic force.

Our investigations confirm that the best progression rates are achieved when the system response is periodic and the frequency of the response is the same as the frequency of the applied dynamic force, and the value of the static force is smaller than the amplitude of the applied dynamic excitation. This result is valid for both models considered. Also in both cases, zero progression rates are obtained for lower values of the excitation amplitudes and the average progression increases with the increase in the dynamic amplitudes. Both models also predict zero progression rates at the higher excitation frequencies.

Based on the analysis undertaken, it can be concluded that the low dimensional model provides good estimates of the optimal static force and the amplitude of the dynamic force, and it could be used for the operational control of the drilling system to adjust the loading parameters while drilling through different formations. The choice of the optimal frequency, however, should be made based on the predictions of the more detailed model of the drilling system as additional degrees of freedom significantly influence the structure of the internal resonances and they should be taken into account.

1. Introduction

The idea of utilising impact energy to drill rock formations has been tried by the engineering community since the late 1940s, when a number of tools were developed known as downhole hammers, percussive hammers, percussive drills and others [1]. They all had a similar operating principle, where a compressed-air or hydraulically operated piston impacts upon a drilling rod (or series of rods) transferring the potential energy into kinetic energy of the drill-bit [2]. As a result, rocks are chipped and crushed and the drill-bit together with the drill-string penetrate into the rock. To further enhance penetration rates, rotary action may be superimposed upon the percussive motion of the drill bit. A fresh area of the rock surface is then presented to the drill-bit at each successive blow provided that cuttings are being effectively removed from the drilling zone.

The performance of percussive hammers [1] has been studied extensively both in the laboratory and in the field. Guarin et al. [3] presented one of the first reports on the usage of the rotary percussion-drilling technique to drill an almost 4 km deep well. The authors considered the effect of weight on bit (WOB) and rotary speed upon the tool performance in various formations, and also studied the behaviour of the various drill-bits during percussive drilling. In general, substantial improvements in penetration rates were achieved in comparison with rotary drilling. In 1958 Topanelian [4] conducted an experimental study in the laboratory investigating the effect of the frequency of percussive drilling in the range from 5 to 17 Hz (low frequency range) on granite blocks. In these experiments the drill-bit was held stationary and the test block was rotated and forced upwards by a hydraulically lifted rotary table. It was concluded that using percussive action more than doubled the penetration rate normally produced by the static WOB. In 1964 Bates [5] presented some field results of percussive air drilling. He has demonstrated that the pressure to operate the percussion tool was the most significant single factor affecting the progression and that selection of the bit was very important for

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the operation. Further field results were presented by Smith and Kopczynski [6] who also concluded that “air-rotary-percussive drilling is a valuable tool for the industry” and requires further development and optimisation.

The fundamental mechanisms of percussive drilling were investigated by a number of researchers including Simon [7,8], Hustrulid and Fairhurst [9–12], Lundberg [13–17], Franca and Weber [18,19], and the Centre for Applied Dynamics Research in Aberdeen [20-26]. Simon [7,8] considered the energy in the stress wave in the drill steel produced by the striker impact together with the energy required for breaking the rock and computed the efficiency of stress wave energy conversion into work done by the bit on the rock. He also discussed the possibilities of improving utilisation of the energy to drill rock. Hustrulid and Fairhurst analysed the efficiency of impact energy transfer from drill to rock both theoretically [9] and experimentally [11]. They also studied the force–penetration relationship both in static and dynamic loading conditions using indentation tests and a “drop test” [10]. In [12] a series of full-time drilling tests made using three different percussive machines were presented, where blow energy, blow frequency, rotational speed, thrust, penetration rate, and the impact-produced strain waves were measured. It was shown that the minimum thrust required for optimum energy transfer to the rock is a function of the blow frequency and the initial and rebound momentum of the piston, the latter depending on the incident waveform and the force–penetration curve. Aspects of energy conversion, energy transfer and efficiency were considered in [13–17] by Lundberg and his co-authors, who also compared the efficiencies of different percussive processes in these papers. With the exception of [16], where dynamic 3D models were used, wave phenomena in drills have generally been studied using 1D wave theory.

Drifting oscillator models suitable for percussive drilling dynamics description were introduced in [20,22] and have been extensively studied in the past, see for example [23,24], to find the optimum characteristics of the applied static and dynamic forces. In these studies the impacted media was represented by the so-called sliders which provided the contact force acting on the drill-bit during the interactions. These models were developed further in [25,26] to take into account the influence of contact geometries and the governing force–displacement relationship during the crashing stages of the interactions.

Franca [18] conducted a series of experiments on an in-house designed rotary-percussive drilling rig and proposed a phenomenological bit-rock interaction model for rotary-percussive drilling aiming to obtain quantitative information from drilling data related to rock properties, bit conditions and drilling efficiency. More recently Franca and Weber [19] conducted experimental and numerical studies of a new resonance hammer drilling model with drift and showed that the behaviour of the system may vary significantly from simple periodic regimes to chaos. Wiercigroch et al. [21] presented extensive studies of ultrasonic percussive drilling with diamond-coated tools in the laboratory conditions on rocks such as sandstone, limestone, granite and basalt. The studies aimed to explore the applicability of this technique to downhole drilling and were supported by the development of mathematical models capable of describing the main phenomena occurring during drilling.

Despite these technological advances, significant scientific interest and activities in this area, there are still a number of challenges to be addressed for the technology to become the norm in the industry [1,27]. An extensive research programme conducted in the University of Aberdeen in the last few years aims to develop the Resonance Enhanced Drilling (RED) technique [28] and this paper will present some of the results of the mathematical modelling and analysis obtained during this project. The main idea behind this technology is to apply an adjustable high frequency dynamic stress (generated by axial oscillations) in combination with rotary action in order to enhance the penetration rates by creating resonance conditions between the drill-bit and the drilled formation. This resonance needs to be maintained for varying drilling conditions by adjusting the frequency and amplitude to produce a steadily propagating fracture zone and it is particularly beneficial while drilling the hard rocks.

An experimental rig shown in Fig. 1 was designed and manufactured to explore these ideas. To assist data gathering during experiments, in the current rig the vertical oscillations of the drill-bit generated by a PEX magneto-strictive device and static weight on bit provided by the hydraulic cylinder are separated from the rotary motion of the specimen which is supplied by the rotating table of the vertical lathe. This arrangement allows for a significant simplification of the rig instrumentation but maintains the combined rotary percussive action applied at the rock/drill-bit interface.

This paper is focussed on the modelling of the percussive component of the system dynamics and it presents the results of the numerical analysis and a comparison of the two models. The first one is a newly developed model of the experimental rig and the second one is a simplified low dimensional model [22] created to describe the dynamic interaction between the drill-bit and the drilled formation. Our aim is to identify how the complexity of the model including additional degrees of freedom influences the prediction of the optimal loading parameters. The rest of the paper is organised as follows. In Section 2 the mathematical model of the experimental rig is introduced and the equations of motion are presented. The next section describes typical behaviour of the system and examines the influence of the external force parameters on the system dynamics. Section 4 presents the comparison between the predictions of the optimal loading calculated according to this new model and the model introduced in [22].

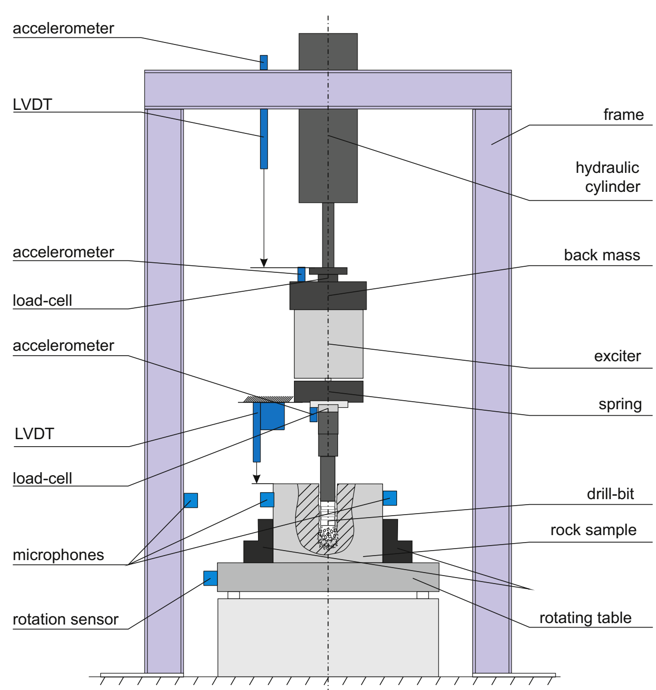

Fig. 1. Schematic of the experimental rig. The drill string consists of a number of elements including exciter (PEX magneto-strictive device) providing the dynamic external force, two structural springs and back mass to control vibrations within the system, and a drill-bit. The static force is applied using the hydraulic cylinder which drives the system downwards when the rock is broken and the progression takes place. The rotary action is generated through the rotating table where only the rock specimen is rotated. As indicated there are a number of load-cells, LVDTs and other sensors to monitor the system dynamics.

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