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Dynamic method of stiffness identification in impacting systems for percussive drilling applications

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ABSTRACT

This paper introduces a dynamic method for the stiffness identification of an impacted object via analysis of its corresponding impact duration. To accurately detect the impact durations from experimental signals, nonlinear time series methods are applied. Two low-dimensional dynamical systems, including a piecewise-linear impact oscillator and a rock impacting system, are studied experimentally and numerically to demonstrate the proposed method. Meanwhile, the analytical prediction of the impact duration for the period-one one-impact motion is developed. The results of both systems indicate that, for a certain stiffness, the impact duration of the period-one one-impact motion is nearly constant. The higher the stiffness, the lower the impact duration. This monotone correlation provides a mechanism to estimate the stiffness of the impacted object once the impact duration has been accurately detected. The developed method can be used to optimise percussive drilling parameters.

1. Introduction

Impact is the main mechanism for generating rate of penetration (ROP) in many published percussive drilling applications. Percussive drilling, in contrast to conventional rotary drilling, mainly relies on the accumulated kinetic energy during the falling process to force a drillbit into rocks and form a crushed zone beneath the contacting surface. This mechanism provides two advantages when compared with rotary drilling. Firstly, its kinetic impact load is much higher than the load generally achieved in rotary drilling; hence, percussive drilling can be more efficient when drilling hard rocks. Secondly, for percussive drilling, after an impact, the drillbit rebounds immediately, separating the drillbit from rock until the next impact. Statistically, the contact duration in percussive drilling is 2% of the total operational duration, which is substantially less than that in rotary drilling [1]. The shorter the contact duration, the less abrasive wear of drillbit. However, pure percussive drilling has been proved to have a low efficiency in actual drilling applications; since repeated impacts can not further crush the impact zone, but compact the rock fragments if they are not removed in time. Under such circumstances, percussion is naturally considered to co-operate with rotation, i.e., rotary-percussive drilling. Rotary-percussive drilling is expected to combine the advantages of both drilling methods, to further stimulate the potential of drilling efficiency. Specifically, the percussion builds a crushed zone beneath the impact area, and then the rotation cuts and shears the fractures initiated by the percussion, simultaneously removing the rock fragments.

The main purpose of developing the rotary-percussive drilling is to improve drillbit performance and increase ROP [2–4]. Hustrulid and Fairhurst comprehensively studied the percussive drilling of rocks, including the basic theory of percussive

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drilling [5], the force-penetration relationship of rock, and the specific energy determination [6]. They also carried out experiments to verify their theories [7], and mentioned the applications of their model in actual rock drilling [8]. Subsequently, the energy transfer in percussive rock destruction was considered by Lundberg, who also compared the efficiencies of different percussive processes [9–11]. Powell et al. [12] performed a field experiment, where they tested a percussion drilling system combined with different hybrid polycrystalline diamond compact (PDC) bits, showing the ROP increased over 100%. The latest progress of the rotary-percussive drilling comes from the Resonance Enhanced Drilling (RED) project [13,14], which is also the motivation of the present work. RED aims to superimpose axial drillbit vibrations upon normal rotary drilling to optimise ROP. This is done by means of a controlled resonance in the borehole. However, due to the heterogeneity and anisotropy of formations, the parameters of axial vibration need to be adjusted so that the resonance conditions can be maintained. This requires a real-time monitoring of the properties of the drilled formation, which is a key aspect within the RED technology. Logging-while-drilling (LWD) [15] is a mature technique for monitoring the drilled formation in real-time. Its measurements include natural gamma ray, neutron porosity, resistivity, sonic speed, nuclear magnetic resonance, and seismic while drilling, etc. Among the variety of the logging measurements, the dynamic responses of the bottom-hole-assembly (BHA) do not attract sufficient attention, although they are beneficial for formation evaluation. The main reason is the limitation of data transmission rates. A large volume of real-time data are necessary for the analysis of the BHA dynamics; however, the data transmission rate of mud-pulse telemetry (MPT) [16] is relatively low, typically as low as 1.5–3.0 bits per second. For electromagnetic telemetry (EMT), data transmission rates of up to 10.0 bits per second can be achieved; however, EMT falls short when drilling exceptionally deep wells, and the signal decays rapidly in certain types of formations, both conditions can cause EMT occasionally to lose the ability of data transmission [17]. As the development of the data transmission techniques, reliable and high-speed telemetry methods make the transmission of a large volume of real-time dynamic data possible. Especially, the newly developed wired drill pipe telemetry [18,19], whose data transmission rates can be upwards of one megabit per second, can provide more than sufficient data support for dynamic analysis. The ideal condition for RED is to apply the collected dynamic response of the drillbit to identify the stiffness of the drilled rock. This stiffness depends primarily on the in-situ elastic modulus of the rock and the contact area of the drillbit.

The drillbit–rock axial interaction can be modeled by an intermittent impact system, e.g., a harmonically forced impact oscillator interacting with an elastic constraint. Many previous investigations have revealed a rich bifurcation structure for this or similar systems [20–22]. Okolewska et al. [23] formulated the energy dissipation during impacts and mentioned the method to calculate the impact duration according to the natural period of the oscillator-base system. Pavlovskaia and Wiercigroch [24] separated the oscillation from drift by using relative displacements, based on which Páez Chávez et al. [25] analysed its bifurcations using a computational package TC-HAT [26]. In order to simulate the mechanical characteristics of rock deformation under intermittent contacts, Ajibose et al. used a solid mechanics approach to model the loading and unloading phases of rock contact [27], and demonstrated the correlation between contact force and indentation via quasi-static rock deformation tests [28].

Time series methods are applied in this paper since only limited measurements can be obtained during experiments. Essentially, time series analysis is a sort of data expansion, under which the characteristic parameters of a system can be explored. Nonlinear time series analysis comprises a set of methods to extract dynamic information through reconstructing the full dynamics of a system from a single time series [29]. The basic idea behind this method is phase space reconstruction, the purpose of which is to expand a certain variable to a multivariate state space as a representative of the original system. Nonlinear time series analysis was first proposed by Packard et al. [30] and then formalized by Takens [31]. The fundamental theories and techniques of nonlinear time series analysis have been introduced by Kantz and Schreiber in their book [32], and they also developed a software package TISEAN [33] to fulfil the functions mentioned in their book. The standard strategy for phase space reconstruction is delay coordinate embedding; a number of methods have been developed to estimate the embedding parameters. The first minimum of the average mutual information [34] is often used to determine the time delay. Kennel et al. [35] suggested the false nearest neighbour analysis to determine the minimal embedding dimension. Invariant quantities of a system, such as Lyapunov exponents [36], fractal dimension [37] can be calculated, to understand the system state. Recurrence plots [38] are used to detect determinism and stationarity, due to their advantage of intuitively displaying all correlations in a two-dimensional plot.

This paper is organized as follows. Section 2 introduces impact duration detection using nonlinear time series analysis and tangent vector analysis. The modulus and direction gradient of the reconstructed tangent vector are defined to recognise impacts. Section 3 discusses an analytical prediction of the impact duration of the period-one one-impact motion based on the 1-DOF impact oscillator. The corresponding numerical simulation and experiment verify the analytical prediction. The correlation between the stiffness of an impacted beam and the impact duration is explored. In Section 4, a rock impacting system which has $2\frac{1}{2}$-DOF [39] is studied. Analytical predictions, numerical simulations and experiments are discussed. The loading and unloading stiffnesses of impacted rocks are estimated according to the detected loading and unloading durations, and the relative estimation errors are analysed subsequently. Concluding remarks are provided in Section 5.