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MINIMISING THE MECHANICAL SPECIFIC ENERGY WHILE DRILLING USING EXTREMUM SEEKING CONTROL

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Abstract. *The mapping of velocity (rate of penetration and RPM), to torque-on-bit and weight-on-bit varies with the design and wear status of Impregnated Diamond (ID) drill bits. Benchmarking of ID drill bits must consider this to avoid biasing. Minimising the mechanical specific energy achieves this, but requires continual monitoring as the drill bit wears. To automatically do so, extremum seeking control was used by inputting a perturbation in the penetration per revolution to estimate the local gradient of the mechanical specific energy, and drive the system to the minimum mechanical specific energy. Results indicate that this control method is stable, and hence can be used in the benchmarking of different drill bits.*

1 INTRODUCTION

Although varying from driller to driller, on some level, the selection of an Impregnated Diamond (ID) drill bit is typically weighed up in terms of the rate of penetration versus wear rate. Generally, benchmarking of these drill bits is conducted by imposing a fixed weight-on-bit or penetration per revolution, and then monitoring its wear, and rate of penetration or weight-on-bit over time [1]. However, this is not ideal as ID drill bit performance varies with weight/penetration per revolution, and is dependent on the balance between diamond and matrix wear rates [2]. Therefore, benchmarking in this fashion can lead to a biased evaluation of a ID drill bit's performance. To avoid biasing imposed by the current method, an alternative approach is proposed to evaluate ID drill bits based on their performance at operating parameters corresponding to the minimum mechanical specific energy, which has been shown to result in sustainable drilling, without excess polishing or matrix wear. However, the challenge is in identifying the operating parameters that result in the minimum mechanical specific energy, and accounting for the fact that they may change as the drill bit wears.

This paper presents a technique to automatically adjust the penetration per revolution, for a constant RPM, to find and maintain the mechanical specific energy at a minimum using extremum seeking control [3].

2 METHODS

The mechanical specific energy, e, is defined as the work done per unit volume of rock drilled. It is given by the following [4]:

$$e = \frac{\tau\omega + Fv}{Av} = \frac{1}{A}\left[2\pi\frac{\tau}{d} + F\right] \tag{1}$$

where τ is the torque-on-bit, ω is the drill bit's rotational speed, F is the weight-on-bit, v is the drill bit's downward velocity, A is the cross-sectional area of the hole, and d is the penetration per revolution of the drill bit.

The typical shape of the mechanical specific energy with respect to penetration per revolution is shown in Figure 1. At very low values of penetration per revolution, the mechanical specific energy is very large given the cutting component is smaller relative to the frictional component, and hence efficiency is worse.

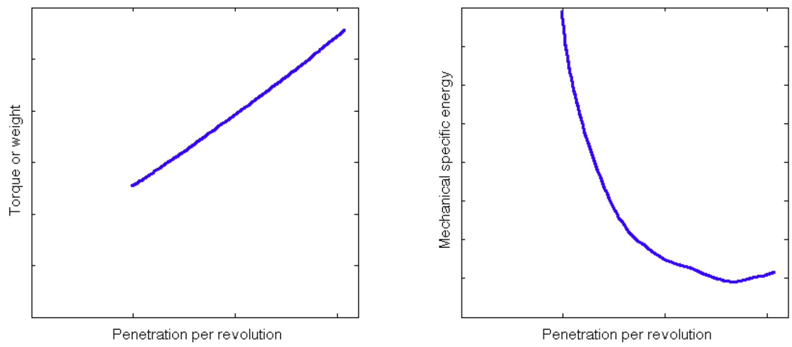

Figure 1: Typical shape of torque and weight (left), and the mechanical specific energy (right) with respect to penetration per revolution

To use extremum seeking control, the derivative of Eq. 1 must be estimated with respect to the controller output, namely the penetration per revolution, d, using a perturbation in the output, and the response should ideally be linear. However, as can be seen from Figure 1, the mechanical specific energy is not linear (nor should it be for a minimum to occur), whilst τ and F are quite strongly linear. Therefore, it is preferential to estimate the derivative from it's individual constituents, as per Eq. 2.

$$\frac{de}{dd} = \frac{1}{A}\left[2\pi\left(\frac{\tau'}{d} - \frac{\tau}{d^2}\right) + F'\right] \tag{2}$$

To estimate the terms in Eq. 2, it must be considered that a phase shift can exist between the input d, and the outputs τ and F, and that it can vary over time. This phase shift can be due to drill string dynamics, the angular separation between cutters (diamonds), etc. To allow for an unknown phase shift, frequency response function estimator methods can be used [5]. The gain between the input d and outputs τ and F at the perturbation frequency is then used to estimate τ' and F', respectively, and mean over the analysis window used to estimate d, τ, and F.

Given it is the derivative estimate that acts as the extremum seeking controller's feedback, it is useful to modify it in two ways to aid in maintaining stability and to help maximise controller performance.

The first is to make the controller feedback independent of any scaling of e, which could be caused, for example, by a change in rock formation. To do so, it is preferable to divide Eq. 2 by Eq. 1 giving the fractional rate of change in e for a small change in d:

$$\frac{de}{dd}\frac{1}{e} = \frac{1}{d}\frac{2\pi\left(\tau' d - \tau\right) + F' d^2}{2\pi\tau + Fd} \tag{3}$$

The second is to help linearise the relationship between controller output and controller feedback so that the gain is approximately constant regardless of distance from the minimum. For example, as $d \to 0$, Eq. 3 will approach infinity. Therefore. it is preferential to multiply Eq. 3 by d, as in Eq. 4, which is the final form used as the controller feedback for the extremum seeking controller:

$$Q = \frac{de}{dd}\frac{d}{e} = \frac{2\pi\left(\tau' d - \tau\right) + F' d^2}{2\pi\tau + Fd} \tag{4}$$

To choose a suitable perturbation frequency, a chirp penetration per revolution input was used while drilling. This allowed the determination of both the range of frequencies that had a gain representative of the static (0hz) gain, and which had a suitable signal to noise ratio.

To design the controller, the process was modelled by a moving average filter (due to the frequency response function estimation method used) with a static (0hz) gain, k, the latter being determined by stepping d, measuring Q, and then least squares fitting a 1st order polynomial to the data. Then, considering that the minimum e location may move as the drill bit wears, a double integrator with roll off was used for the controller. The final form of the controller (shown in Eq. 5) had a modulus margin of 0.71 to give some degree of stability robustness against discrepancies between the assumed process model, and the actual process.

$$C = \frac{0.5}{k}\frac{\left(s + \frac{2\pi}{4nT_p}\right)^2}{s^2} \tag{5}$$

where s is the Laplace variable, n is the number of perturbation periods used in the estimation of the parameters in Q, and T_p is the perturbation period.

To test the extremum seeking controller, an initial penetration per revolution was set that was known to be well below that corresponding to the minimum mechanical specific energy, and then the controller allowed to optimise the penetration per revolution while drilling through approximately 300mm of rock.

3 APPARATUS AND MATERIALS

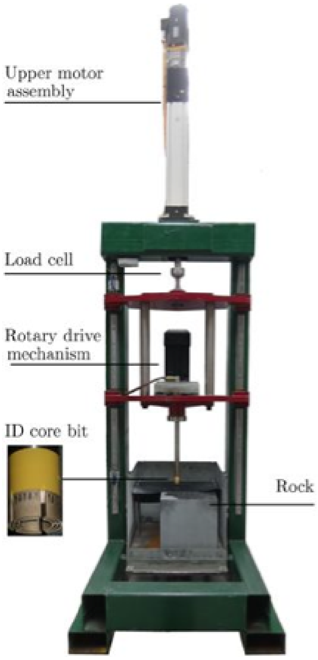

Figure 2: Echidna, a laboratory drill rig that operates under position feedback control, and has an open-loop bandwidth of approximately 25hz for both the rotary and linear penetration

A closed loop position controlled drill rig known as "Echidna" was used to impose a set RPM and penetration per revolution while drilling into rock by electronically gearing the linear (penetrative) motion to the rotation. Motion is achieved using two servo-motors with feedback to maximise the possible precision from each axis. Sensors are used to accurately measure weight and torque.

Operating parameter	Range	Precision
Rate of penetration (mm/s)	0.1 to 20	$\pm$ 0.05
RPM	9 to 1800	$\pm$ 4.5
Torque (Nm)	$\pm$ 94	$\pm$ 0.1
Weight (kN)	$\pm$ 25	$\pm$ 0.02
Drilling fluid flow rate (ltr/min)	3 to 30	$\pm$ 1

Table 1: Echidna operating parameters.

This study was performed using a soft matrix ID core bit with 21.7mm inner diameter and 36mm outer diameter. The granite drilled was American Black granite, which had a compressive strength of 300 MPa, a quartz content of 3%, and a Mohr's hardness of 3.5. While drilling, water was used at the drilling fluid at a flow rate of 10 ltr/min.

4 RESULTS

To identify a suitable perturbation frequency, an up-chirp signal was used (see Figure 3). Above 0.75hz, the gain and phase become increasingly noisy, and began to depart from the static (0hz) gain values. Furthermore, there was a step decrease in coherence above 0.75hz. Therefore, a perturbation frequency of 0.5hz was chosen to be used with the extremum seeking control algorithm.

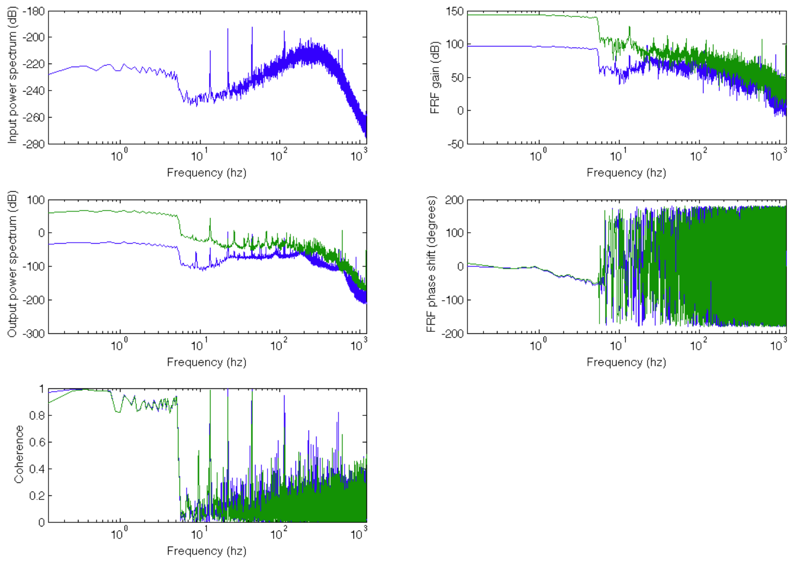

Figure 3: Up-chirp response used to identify a suitable perturbation frequency (50 μm/rev amplitude, 60 μm/rev offset, 800 RPM)

To identify the process static (0hz) gain, the penetration per revolution was stepped over a large range to encompass the minimum mechanical specific energy, and Q calculated at each step (see Figure 4). The result was relatively linear with a 0.8 coefficient of determination, R^2, and the least squares fit slope found to be approximately k = 4700 rev/m.

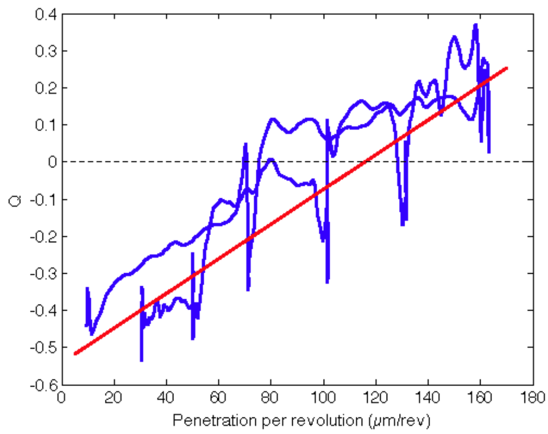

Figure 4: Static gain identification showing approximately linear response between d and Q. A 0.5hz, 10 μm/rev amplitude perturbation was used, and the drill bit rotated at 1600 RPM.

To test the extremum seeking control algorithm an initial penetration per revolution of 50 μm/rev was chosen, which was below that corresponding to the minimum mechanical specific energy, and then the mechanical specific energy recorded as the extremum seeking controller was allowed to optimise the penetration per revolution (see Figure 5). Although it is not possible to know what and where the minimum mechanical specific energy is at any point in time, two observations can be made. One, the extremum seeking controller appears to maintain the penetration per revolution about a point that appears to correspond, on average, to the minimum mechanical specific energy. Two, when comparing the penetration per revolution and the various minima observed in the time evolution of the mechanical specific energy, it is observed that the neither the minimum mechanical specific energy, nor its location in the penetration per revolution space, is constant in time.

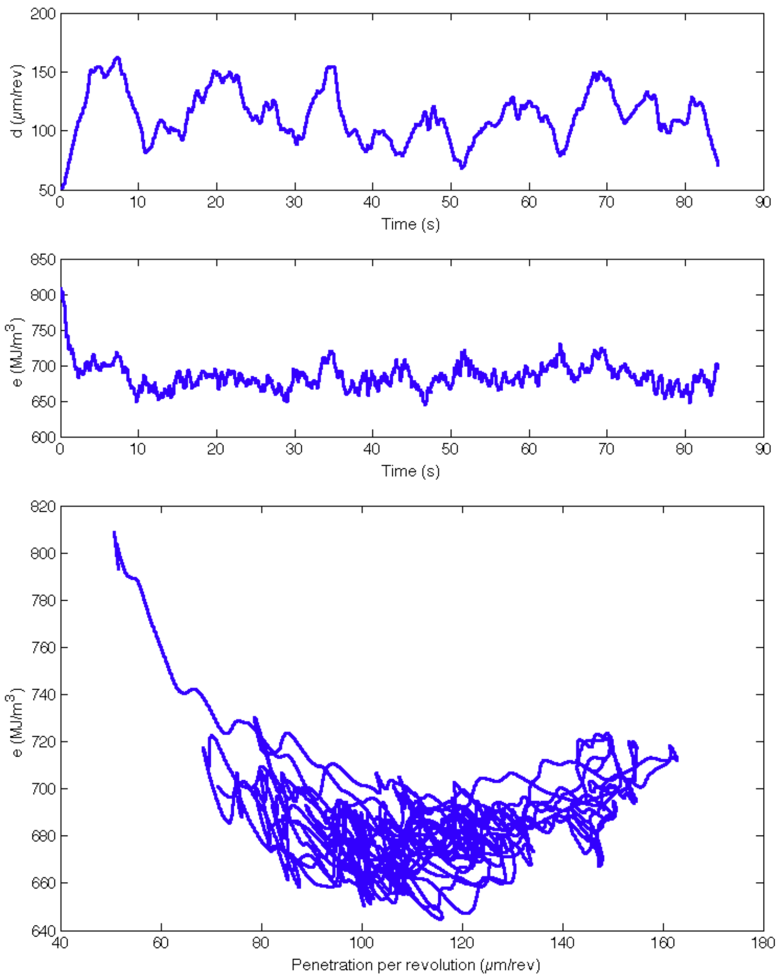

Figure 5: Extremum seeking control test results showing input d (penetration per revolution) and output e (mechanical specific energy) after using a notch filter to remove the 0.5hz, 10 μm/rev amplitude perturbation, and a 0.5hz low pass Bessel filter to help smooth results. Test was conducted at 1600 RPM.

5 CONCLUSIONS

- This work has proven the potential of using extremum seeking control to maintain the minimum mechanical specific energy while drilling, and therefore ID drill bit performance (in terms of weight-on-bit, penetration per revolution, and wear rate, etc) can be evaluated under this operating condition condition.

- The minimum mechanical specific energy is not constant in value, nor fixed in the penetration per revolution space (potentially due to the continuous change of the cutting face due to wear), which further justifies having a testing condition that adapts to these changes.
- The design of the controller feedback resulted in a fairly linear response, which is ideal as it allows linear controller design techniques to be used, which are well established.
- There are challenges in calculating the penetration per revolution using sensors with analog output due to noise, even if the measurement technique itself is sufficiently accurate. This is due to the very small displacements that must be measured relative to the overall measurement range. For this reason, sensors with a digital output should be used in measuring these very small displacements.

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