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Push-and-Twist Drillstring Assemblies

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ABSTRACT

Deep drilling using a rigid drillstring requires the assembly and disassembly of multiple drill pipes. The interfaces between these pipes provide a challenge for automation because they must transmit large drilling forces and movements while, at the same time, minimise the actions and forces that are needed to make or break the interface. A geometry which can address these requirements has been suggested by the authors. This approach would use a push-and-twist bayonet system to engage drill pipes, with torque transmission through the bayonet studs. A variety of L-shaped and T-shaped bayonet paths have been proposed to ensure that separation of specific drill pipes can be achieved through a combination of clockwise and counter-clockwise rotation and single-point clamping. Sustained drills into a variety of media are used to show that percussive impulses are transmitted across the interface, whilst ensuring that the drill interface is able to withstand the shock loading associated with hammer-drilling. These tests are repeated and contrasted to control experiments using a single-piece control drillstring, which allows the performance of the interface and any degradation over time to be quantified. Results suggest that the bayonet-style connection performs well with no significant performances losses encountered or structural degradation noted.

INTRODUCTION

As robotic spacecraft seek to explore ever deeper beneath the surface of the extra-terrestrial bodies within our Solar System, more capable tools are required to overcome the presented challenges. The ultrasonic-percussive drilling technique, currently under development by both the University of Glasgow as part of the Ultrasonic Planetary Core Drill (UPCD) project (Timoney, 2015) and NASA JPL, the innovators of the technique (Bar-Cohen, 2000), offers a ‘low footprint’ approach to the challenge of planetary drilling. The percussive nature of the technique, whereby terrain breaking occurs through a compressive overstress at the bit-rock interface, differs from rotary drilling, where grinding dominates. As such, the ultrasonic-percussive technique has been proven experimentally to operate successfully with levels of applied weight-on-bit (WOB) up to an order of magnitude less than conventional rotary systems. As the WOB is typically provided by the weight of the host robotic lander or rover, a factor which is limited by the low levels of gravitational acceleration experienced on the extra-terrestrial body, a reduced WOB demand will ensure that the drill system is compatible with even the most lightweight of landers.

In order to achieve greater sampling depths, a multi-bit drill string approach to borehole lengthening was adopted. The basis of this approach is commonplace in terrestrial sea floor applications, though the isolated conditions foreseen in extraterrestrial exploration, and the subsequent need for robotic autonomy, raises some interesting challenges. As is highlighted in literature (Bar-Cohen, 2009), the use of rod drilling, whereby discrete core sections are obtained through the addition of multiple solid rod sections, becomes increasingly laborious as the number of making/breaking operations sharply rises with depth drilled. As each robotic, autonomous connection/disconnection event presents an opportunity for a failure event, it was deemed imperative that the routine used to accomplish drill string assembly/disassembly was as simple as possible and the interfaces between bits be robust. This routine shall adopt multiple hollow rod sections in place of the solid rod sections used in industrial applications. These hollow sections, connected through an interface based on the bayonet connection, will allow sections of cored rock to pass completely through the drill string, and thus significantly reduce the number of operations required to collect core samples. As the ultrasonic-percussive drilling technique relies on harnessing percussive stress waves which are transmitted through the length of the drill string, there was concern raised regarding a potential loss of efficiency when transmitting percussion across the bayonet-style connection interface. This paper shall explore the effectiveness of the bayonet-connected drill bits in delivering impulse to the system by a direct comparison with a single-piece control drill bit, drilling through three specimens of sandstone.

SCIENTIFIC MOTIVATION

A strong demand for ever more capable drill systems has arisen from a continued interest in the astrobiological potential of the Martian subsurface, bolstered by in-situ measurements of radiation levels and remotely sensed data which has finally confirmed the presence of seasonal surface water. A survey of future Mars astrobiological exploration missions currently proposed or in development suggests that the majority of missions shall fulfil one of two possible mission criteria:

1) In-situ chemical analysis of subsurface samples with the purpose of identifying the presence of bio-indicator organics.

2) Subsurface sampling and caching with the aim of returning the collected samples to Earth for detailed sample analysis.

Although core samples are favored for scientific analysis, largely due to the fact that the interior of the core yields a virgin surface, untouched by the drill system itself with intact lithography, obtaining pristine core samples requires a high degree of instrumentation complexity and robotic manipulation. Conversely, collection of powdered samples, pulverized directly at the bit-rock interface using a full-faced cutting bit, allows for a reduction in sample processing complexity, albeit with an added challenge involved in transporting the cuttings to the analysis instrumentation. Mission types which fulfil criterion 1, whereby in-situ analysis is carried out, have greater flexibility in the type of sample to be collected. Flagship missions which typically

benefit from an increased budget and longer development times than their Discovery-class counterparts, may allow the inclusion of a drilling system which captures core samples. The 2018/2020 rover element of the ExoMars mission shall utilize a core drill capable of reaching depths of up to two meters, collecting samples which shall be returned to the surface, pulverized and delivered to the on-board instrument suite for analysis (Winnendael, 2005). The multi-bit drilling system used is complex and will allow for samples to be collected at desired depths through the use of an internal piston-driven shutter which opens an aperture at the bit-rock interface. This aperture modifies the full-faced cutter such that it can accept a core, approximately 10 mm wide by 30 mm long. Lower cost missions, such as the recent, Discovery-class “IceBreaker Life” proposal would utilize a one meter-class, full-faced drilling system mounted on a Phoenix/InSight heritage lander (Zacny, 2014). The mission seeks to explore the ice-bound Mars Northern Polar Regions within an astrobiological context. The drill system proposed would collect freshly drilled cuttings directly from the flights of the auger via a passive brush system used to sweep the cuttings in to a sieve and then a collection scoop. Such a methodology greatly reduces the required drill mechanical complexity, though all surfaces of the sample are exposed to the environment and the drill string itself, potentially degrading scientific value. The in-situ analysis proposed would reduce the impact of any degradation, ensuring that the desired search for organic molecules could be accomplished without the need for core sampling.
Missions which fulfil criterion 2, the collection of samples for future return to Earth, are typically mechanically and operationally complex with multiple elements. The Mars 2020 rover mission shall be the first stage of such a campaign, seeking to obtain core samples from multiple locations which shall be cached, awaiting loading on a Mars Ascent Vehicle at a later stage. Benefiting from heritage attained from the Mars Science Laboratory mission and the use of a robotic arm, the mission aims to recover up to 31 core samples of 50 mm length (Mustard, 2013). Whilst any samples returned from the Mars 2020 mission will most certainly prove highly useful in furthering mankind’s understanding of the geological history of Mars, any such mission is not without limits. As stated in the Report of the Mars 2020 Science Definition Team, optimal samples to be returned would measure > 50 mm, obtained from depths of up to 2 m. Mechanical complexity and operational complexity are stated as the limiting factors to the inclusion of such a drill system onboard the 2020 mission. It is in this niche which the UPCD system seeks to fill. The UPCD system, equipped with an expandable drill string and the ability to collect and cache intact, lithographically pristine cores, hopes to demonstrate a new solution to the problem of deep core sampling and caching.

TEST DRILL BIT DESIGN

The UPCD system must reliable and consistently connect multiple drill bits together to form a drill string whilst still ensuring that the required percussive hammering stresses can be delivered to the bit-rock interface. The connection system chosen is based on the bayonet system and consists of T and L-type grooves, machined in to the drill bits, which act as the ‘female’ component of the connection system. Studs, also machined from solid drill bits, act as the 'male' connector piece. Figure 1 details an example of a typical disconnection operation.

The lance component, the interface between the rotating, shaft of the drill tool and the drill string itself, provides a means of connecting and disconnecting the drill tool with the drill string. In order to disconnect the uppermost drill bit from the drill string for caching, the lance requires a T-style groove. This groove geometry allows the drilling rotation to be reversed whilst ensuring that the lance remains connected to the uppermost drill bit. As all drill bits are machined with an L-style groove, the drill bit to be cached can be disconnected from the rest of the drill string through the combined action of the Terrain Clamp and a reversed drilling direction. In order to ensure that the grooved mating surfaces remain free of dust and larger particles during operation, essential if they are to function reliably, it was decided that the grooves would be machined within the interior of the drill bit by Electric Discharge Machining (EDM).

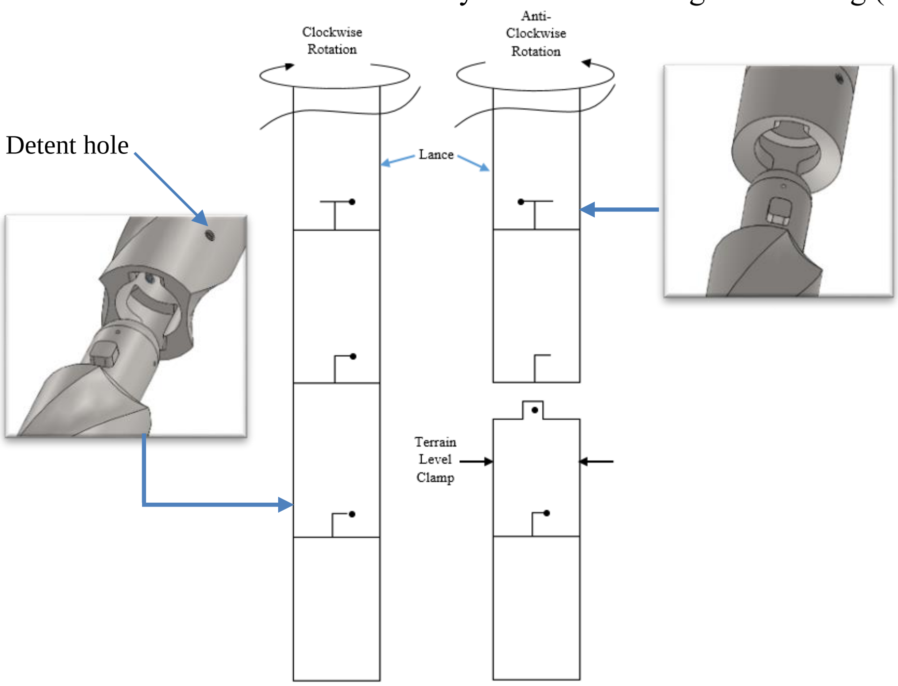

Figure 1: Drill Bit Disconnection Procedure

To ensure that the percussion-induced stress wave is not impeded by the use of the bayonet-style connection as it travels through the drill string, experimentation was required in order to establish if there would be any significant reductions in performance or damage to the studded connector itself. Experiments were performed using a bayonet-connected lance and drill bit and, for the purpose of comparison, a control piece was also manufactured. The control piece consisted of a lance/drill bit machined as a single component, therefore without any bayonet connection. Figure 2 details the two test items.
With the knowledge that contamination would not be problematic in a laboratory set up and to ensure a rapid manufacturing of parts, the bayonet grooves for this series of testing were machined on the exterior of the drill bit using conventional machining

techniques. Furthermore, as the testing was to occur on a horizontally mounted rig to shallow depths, it was decided that the test bits would be manufactured without an auger, typically used to accomplish important role of spoil removal from bit-hole interface (Zacny, 2007), instead relying on the travel of fine grain cuttings out of the hole through a combination of the sonic waves created through percussion (Badescu, 2007) and gravity.

Figure 2: Control (left) and Bayonet-Connected Test Pieces

The drill bits are tipped with tungsten carbide teeth which have been brazed into place. Though tungsten carbide is extremely hard, care was taken to ensure an even wear on the teeth so as to ensure that this variable was controlled.

TEST PROCEDURE

In order to carry out both performance testing whilst providing a proving ground for key technologies critical to development, the UPCD project has constructed a mechanical rig. The rig, detailed in Figure 3, allows a testing variant of the ultrasonic-percussive drill to advance autonomously, utilizing an in-house control algorithm [Li, 2015], in to a rock formation. The control loop requires a pre-set Reference Power Level, derived from the power electronics of the ultrasonic transducer. The power electronics, an off-the-shelf Sonic Systems P100 control unit, drives the ultrasonic piezoceramic rings at resonance in order to maintain a constant output amplitude or power level, compensating for sonic energy transferred to the drill string and rock formation during percussion.

The control loop advances and retracts the linear actuator depending on the power feedback it receives. A rise in power is typically attributable to the drill encountering resistance as it penetrates the formation, whilst a reduction in power suggests the drill has penetrated a given section of the formation and is no longer encountering resistance. If the power feedback is lower than a given minimal power value, typically the pre-set minus ten percent, then the control algorithm will detect that the power being supplied to the actuator has fallen. Upon receipt of this control prompt, the linear actuator will be commanded to advance incrementally further in to the formation.

Conversely, a rise in power to the upper limit, typically seen when penetrating stronger rock formations, will result in an incremental withdrawal of the drill assembly until the power level is within desired bounds. The use of this variation of closed-loop control ensures that the drill will penetrate through the rock formation in an efficient, yet controlled manner, utilizing only a pre-set power level. The Reference Power Levels tested in the experimental campaign were 20, 25 and 30 W to allow for variety in testing.

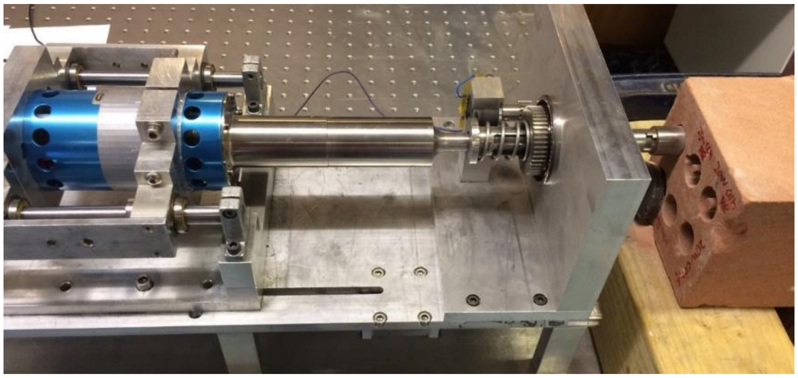

Figure 3: UPCD Test Rig

Although the drill string tested was not machined with an auger for spoil removal, the test rig is equipped with a gearbox, used to slowly rotate the drill string (~20 RPM), via a spline shaft, to ensure the cutting teeth do not embed themselves in the formation, thus halting cutting.

The routine for testing is as follows:

1) Set internal force preload to be used for all tests (10 N).
2) Set Reference Power Level to be tested (20, 25 or 30 W).
3) Select rock formation to be drilled. Attach securely to rig.
4) Attach drill bit to be tested to the threaded spline shaft interface.
5) Reset data collection software and restart control algorithm.
6) Initiate percussion and rotation motor.
7) Ensure nominal action of linear actuator, percussion and rotation.
8) Allow hardware to progress through rock formation for predetermined time.
9) Assess drilling performance: note borehole depth using calipers and drill time.
10) Clean rig and used drill bit. Ensure next drill bit is clean and ready to test.

All data was collected on a laptop and PicoScope oscilloscope and post-processed on MATLAB, utilizing a low-pass filter to aid in signal clarity.
Three sandstones, Locharbriggs, Blaxter and Clashach, were selected for testing as they represent respectively soft, medium and hard rocks (Table 1). Tests were conducted multiple times, along consistent grain orientations, in order to ensure repeatability of results.

Rock Type	**Locharbriggs**	**Blaxter**	**Clashach**
UCS [MPa]	47	55	132
Porosity	18.2-24.9%	20.5%	21.4%
Bulk Density [kg/m^3]	2173	2110	2084
Water Absorption [/wt]	5.7%	6.1%	6.9%

Table 1: Geological Properties of Tested Sandstone Samples (BRE Data Sheets)

EXPERIMENTAL RESULTS

Results obtained through experimental testing and highlighted in Figures 4 – 9 focus on three main repeated Locharbriggs datasets. The graph in the upper-left of each frame, with the signal colored blue, details the P100 power, the power delivered to the piezoceramic rings of the ultrasonic transducer. In the upper-right of each frame is the time history of the Sample Held Power, colored red. The Sample Held Power utilizes the P100 power, integrating it over a period of 1 second in order to establish an average for that second. This integrated power then acts as a direct input to the control system, autonomously controlling the progress of the drill system through the rock formation. If this power value is higher or lower than the limits set by the user as a Reference Power Level the linear actuator will be commanded to advance or retract. The time history extension of the linear actuator is detailed in the bottom of each frame, colored green. Figure 10 compares the results across all three sandstones studied.

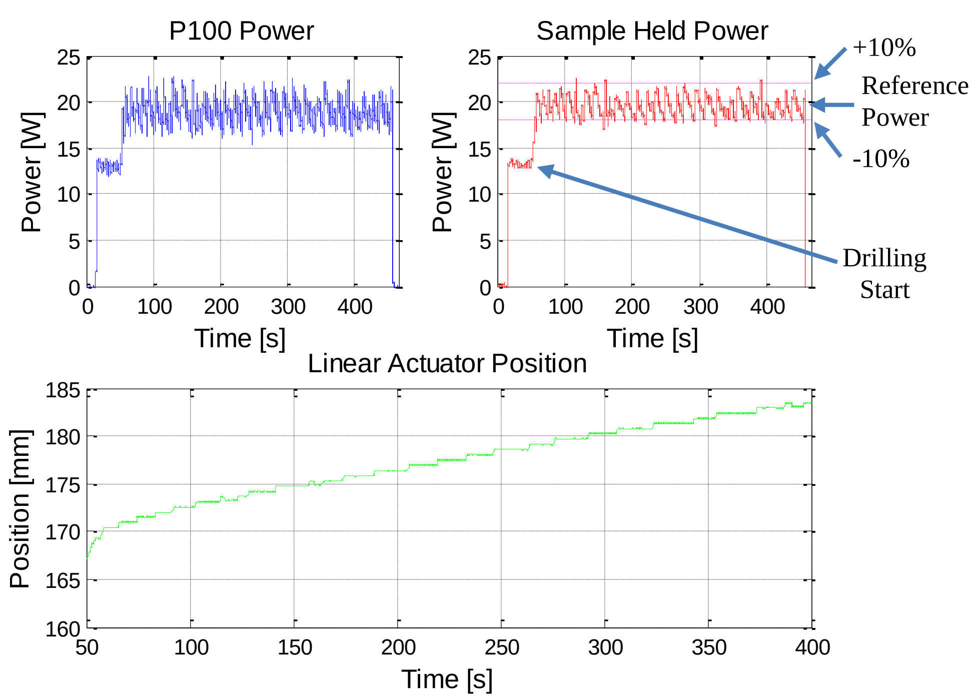

Figure 4: Locharbriggs Sandstone - Bayonet Interface Drill Bit - 20 W

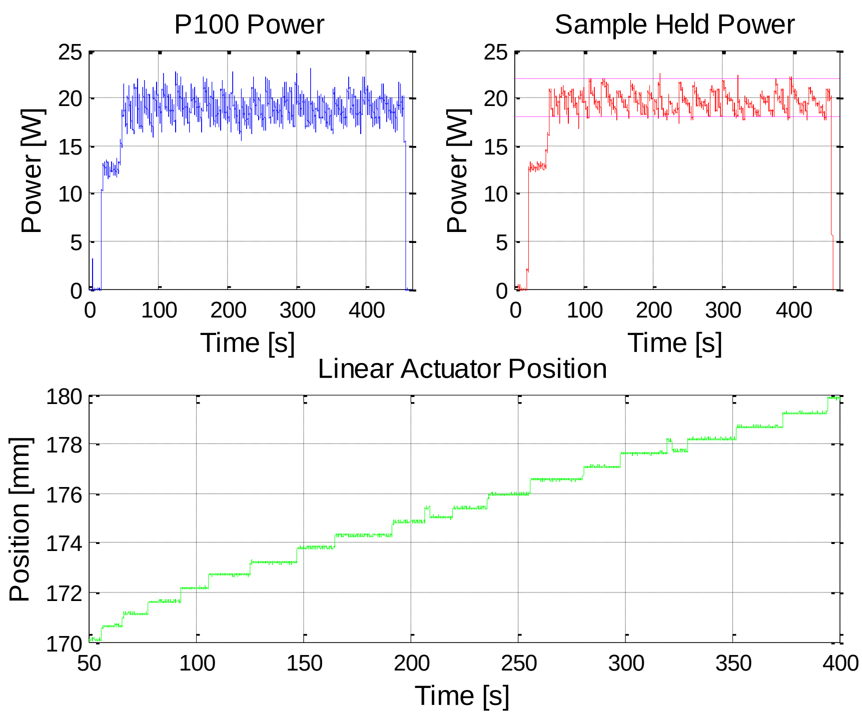

Figure 5: Locharbriggs Sandstone - Control Drill Bit - 20 W

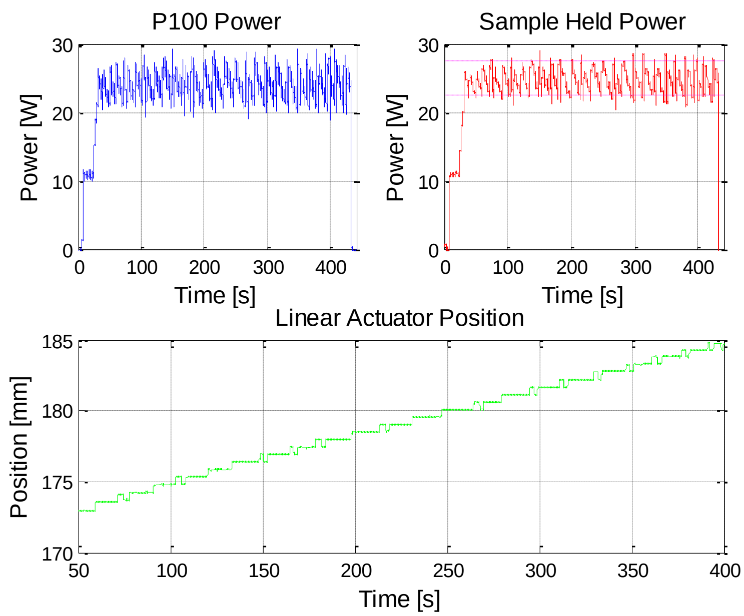

Figure 6: Locharbriggs Sandstone - Bayonet Interface Drill Bit - 25 W

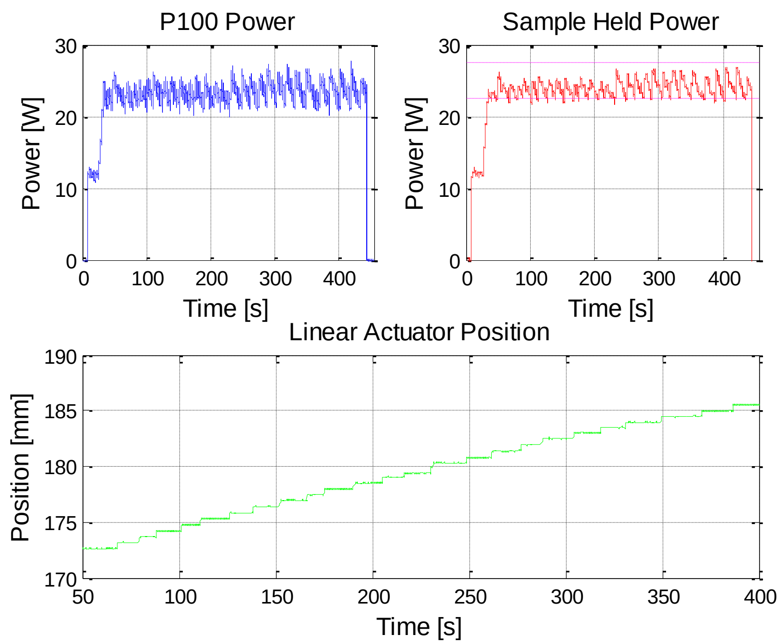

Figure 7: Locharbriggs Sandstone - Control Drill Bit - 25 W

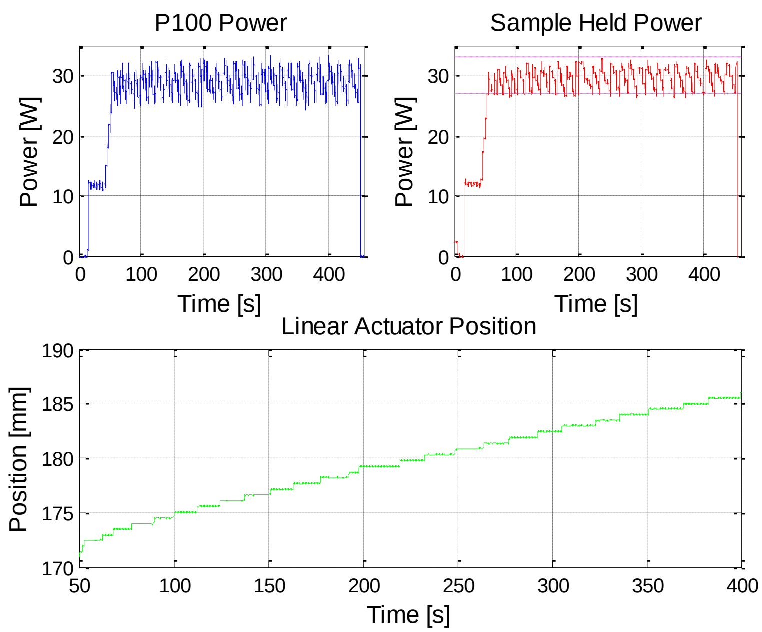

Figure 8: Locharbriggs Sandstone - Bayonet Interface Drill Bit - 30 W

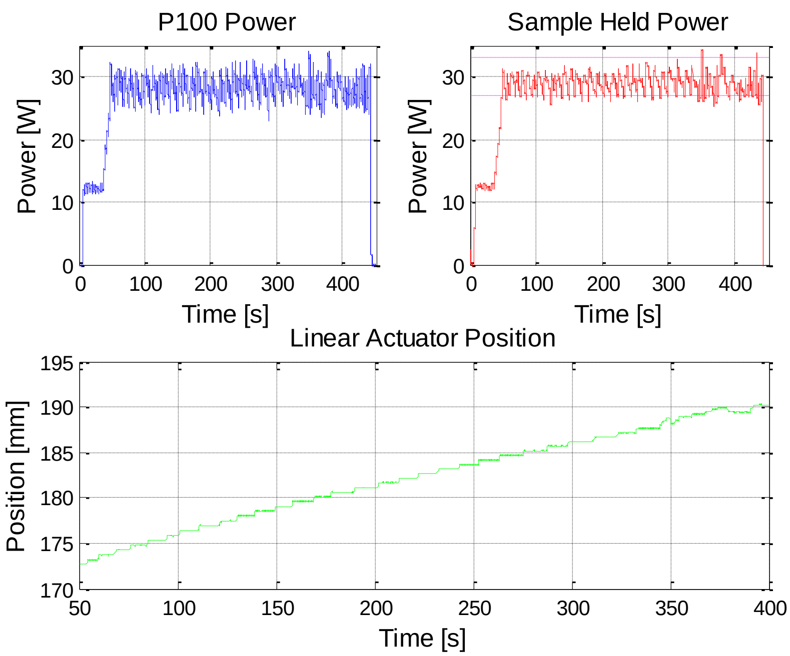

Figure 9: Locharbriggs Sandstone - Control Drill Bit - 30 W

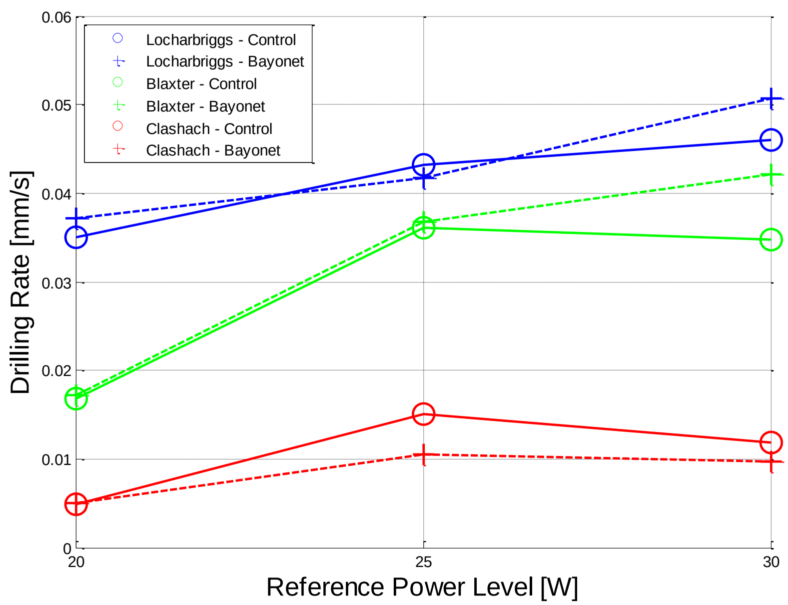

Figure 10: Comparison of drilling rates through different Rock sandstones using a Control Drill Bit and a Bayonet-Interface Drill Bit.

DISCUSSION

Analysis of the results obtained from experimentation allows clear conclusions to be drawn on the use of a bayonet-interfaced drilling bit when utilizing the ultrasonic/sonic percussive drilling technique, combined with rotation, for planetary drilling applications.

Figures 4 and 5 detail data obtained from the testing of the bayonet-interface drill bit and the control bit, respectively, on the relatively weak Locharbriggs sandstone, using a Reference Power Level of 20 W. It is possible to note that the Sample Held Power (SHP) exhibits a similar behavior in both drill bit tests. The relatively little resistance experienced by the drill when progressing through this medium is easily identifiable by the signal which regularly drops below the minimum power level, thus commanding the linear actuator to advance. Furthermore, the Linear Actuator Position (LAP) graph exhibits frequent steps forward, suggesting that the drill is moving deeper into the formation at regular intervals. The 20 W data exhibits relatively few instances of exceeding the SHP maximum value, suggesting that a steady drilling rate could be achieved without a great demand on power. Figures 6 and 7, results from experimentation using the same Locharbriggs rock sample but at a higher power level of 25 W display a slight reduction in similarity in the SHP signal, with the results from the bayonet-interface drill bit generally consuming marginally more power than the control sample, with an increased frequency in the number of sharp power spikes. The LAP data, however, suggests a similar rate of progress through the rock formation. Figures 8 and 9 exhibit further increases in the aggression of the drill as it progresses through the sandstone, observable as an increase in the frequency of the SHP signal. The frequency of power events which have a SHP value lower than the minima value of the Reference Power Level is also increased relative to the 20 and 25 W datasets, resulting in an increased rate of progress through the rock formation. Figure 10 provides a comparison of the control and bayonet results for each rock type at all three Reference Power Levels tested. It can be seen that there is very little deviation in the drilling rates of the 20 and 25W experiments of Locharbriggs and Blaxter, with the bayonet-fitted drill bit outperforming the control piece at the 30W power level of both samples. The 25W Clashach test case sees the control piece outperform the bayonet piece, though a close similarity of the drilling rates of the 20 and 25W cases suggest that the 30W case may be erroneous. Post-testing inspection of the drill bits used showed no major deformation or damage to either test drill bit or the ability to connect and disconnect the parts of the bayonet-fitted piece.

Figure 11: Locharbriggs, Blaxter and Clashach sandstone specimens post-testing

CONCLUSION

The ultrasonic-percussive drilling technique benefits from many of the attributes required for potential use as a future planetary exploration technology. The test campaign documented within this paper resulted in the successful coring of three different specimens of sandstone. Results of these tests are shown in Figure 11. Confirmation that the easily disassembled bayonet-based system used does not limit the percussive capability of the system has been achieved alongside the knowledge that the bayonet interface will withstand the high levels of shock loading delivered through percussive drilling. The authors intend to continue with the development of the UPCD system, reassured by the results obtained.

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