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Auto-Gopher - a wire-line rotary-hammer ultrasonic drill

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ABSTRACT

Developing technologies that would enable NASA to sample rock, soil, and ice by coring, drilling or abrading at a significant depth is of great importance for a large number of in-situ exploration missions as well as for earth applications. Proven techniques to sample Mars subsurface will be critical for future NASA astrobiology missions that will search for records of past and present life on the planet, as well as the search of water and other resources. A deep corer, called Auto-Gopher, is currently being developed as a joint effort of the JPL's NDEAA laboratory and Honeybee Robotics Corp. The Auto-Gopher is a wire-line rotary- hammer drill that combines rock breaking by hammering using an ultrasonic actuator and cuttings removal by rotating a fluted bit. The hammering mechanism is based on the Ultrasonic/Sonic Drill/Corer (USDC) that has been developed as an adaptable tool for many of drilling and coring applications. The USDC uses an intermediate free-flying mass to transform the high frequency vibrations of the horn tip into a sonic hammering of a drill bit. The USDC concept was used in a previous task to develop an Ultrasonic/Sonic Ice Gopher. The lessons learned from testing the ice gopher were implemented into the design of the Auto-Gopher by inducing a rotary motion onto the fluted coring bit. A wire-line version of such a system would allow penetration of significant depth without a large increase in mass. A laboratory version of the corer was developed in the NDEAA lab to determine the design and drive parameters of the integrated system. The design configuration lab version of the design and fabrication and preliminary testing results are presented in this paper.

KEYWORD: Piezoelectric, piezoelectric horn transducers, Life detection, planetary sampling, corer, wireline drill.

1. INTRODUCTION

The acquisition of rock and soil sample plays an important role in NASA's space explorations missions. Tools capable of coring, drilling, and abrading are necessary for such activities. Due to the energy and mass limitations of such missions, the large axial forces and high power consumption of conventional drills are extremely undesirable. In addition, conventional drills operate at greater depth by adding new drill segments on top. This could possibly increase the mass, volume, and complexity of the system. The NDEAA team and Cybersonics address many of these issues with the Ultrasonic/Sonic Drill/Corer (USDC) [1]. Inside the USDC, a piezoelectric actuator generates vibration that propagates through a horn, which then impacts a free-flying mass. The mass then impacts a drill bit introducing stress pulses onto the drill bit, thus impacting and fracturing the rock as the rock's ultimate strain is exceeded. The USDC's key features include lightweight, low axial forces, and the ability to act also as an on-site analyzer [3]. Furthermore, the wire-line drill design of the USDC allows it to operate at depths larger than the drill length without additional drill segments. The focus of this research task is on the development of Auto-Gopher, a rotary-drill design based on the USDC. In addition to existing features of the USDC, the Auto-Gopher incorporates a rotary actuation (Figure 1). As the USDC drills and cores, it will need to periodically be removed from the produced borehole to empty an internal chamber where cuttings accumulate. This gives it the nickname Auto-Gopher.

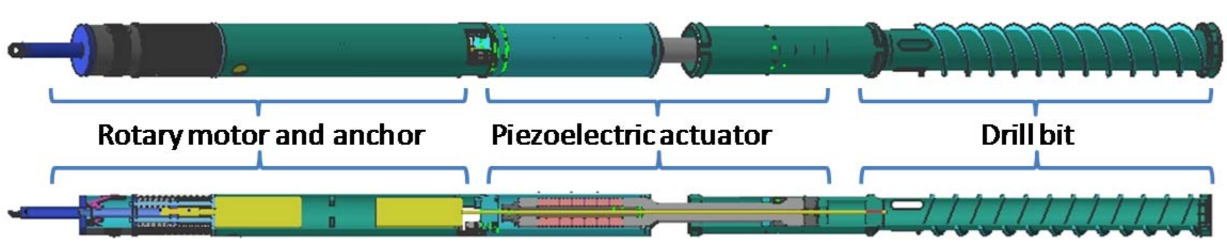

Figure 1 Auto-Gopher solid model and cross section

A laboratory version for testing the Auto-Gopher prototype parameters was designed and built in NDEAA lab as shown in Fig.2 to determine the design and drive parameters of the integrated system. The design configuration, lab version of the design and fabrication and preliminary testing results are presented in this paper.

2. DESIGNS

The wireline Auto-Gopher operation require that the whole body of the drill fits in the hole created by the drill head. All drill components: drill bit, percussive component, rotary component and anchor and linear feed component have to be sized and packaged to fit the cylindrical hole created by the drill bit.

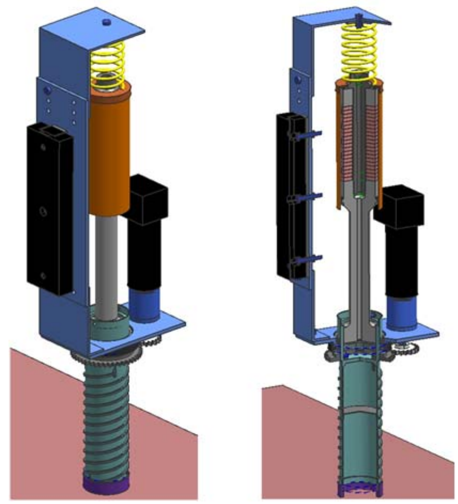

Figure 2 Lab version of the Auto-Gopher solid model and cross section view

The lab version designed and built in our lab needed to determine the optimal design and operating parameters of the percussive component and so it is simpler than the full Auto-Gopher version. All four components are still present but the implementation does not allow deep drilling. For ease of fabrication we chose to use a side mounted rotary component and a linear slide.

The drill bit (Figure 3) is a coring tube with outside flutes and three inner chambers: a core chamber designed to house the core, a cuttings chamber to collect the cuttings created during coring, and a free mass cup for housing the free mass and the piezoelectric actuator horn tip. On the outside is has three flutes that will guide the cuttings into the powder compartment. The active cutting element is a crown threaded onto the bit that can have 3, 4 or 6 carbide cutting teeth. The bits interchangeability is one of the USDC's key features. The USDC provides simple interface to various bits onto a single actuator, thus allowing multiple functions while keeping logistics simple. If a bit is damaged, it can simply be replaced. Such concepts used on the USDC also apply to the Auto-Gopher. Furthermore, studies have shown that an increased drilling rate may be obtained when the bit vibration is combined with rotation [5]. Efforts were spent looking into new bit designs that implement this concept and on fabricating the new bit.

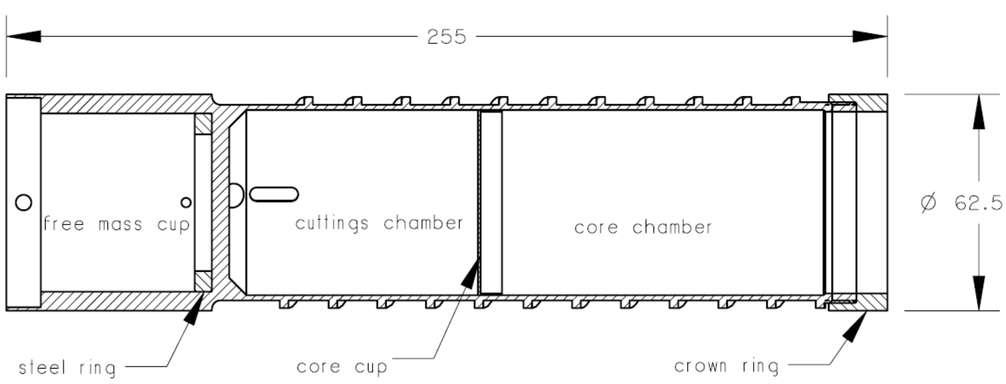

Figure 3 Drill bit assembly drawing

The percussive component includes the piezoelectric actuator, the free mass, and the preload spring. The piezoelectric actuator consists of a stack of PZT rings maintained in compression between a backing and a horn by a pre-stress bolt. The horn has a dog bone shape and amplifies the vibrations of the PZT stack. Its tip acts like a hammer and impacts the free mass that in turn transfers the impact to the bit. The free mass acts as a frequency transformer from high frequency vibration of the piezoelectric actuator to a sonic frequency of 60 to 1000 Hz. For higher impact transfer efficiency the free mass was made out of a high hardness steel as was the the steel ring in the drill bit. As the free mass starts bouncing between the bit and the horn tip a gap is created in the space between the horn tip and drill bit. The preload spring applies a constant force on the actuator and the value of this force controls the size of the gap between the horn tip and the drill bit and hence the frequency of the free mass impacts.

The rotary component (Figure 4) consists of a rotary motor and a set of gears for rotating the drill bit. The main function of the drill bit rotation is to remove the cuttings from the created hole. The motor was mounted on the side of the drill bit for ease of fabrication and design simplification.

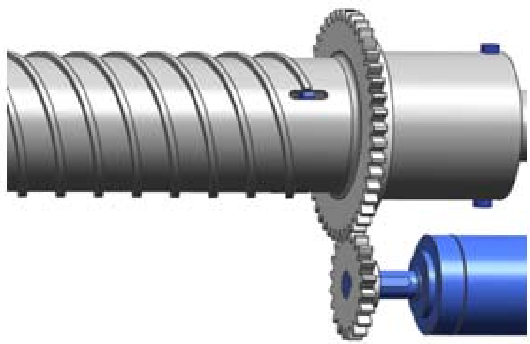

Figure 4: Rotary drive component

To understand the capabilities of the Auto-Gopher, it was also important to have a testing setup with the appropriate preload that allows the designated drilling motions to take place. Hence, a test setup that would integrate the drill bit, percussive and rotary components, maintain an adjustable weight on bit and allow linear feed during drilling was designed and fabricated for this purpose (Figure 2). It consists of an adjustable length bracket attached to a linear slider. The base of the bracket allows bit and rotary motor mounting. The bit mounting allows bit rotary motion and axial limited displacement. The bracket length determines the compression of the preload spring of the piezoelectric actuator. It is adjusted depending on the free mass size, mass, and drill bit mass.A motor and gear set with the desired specifications were selected and purchased to provide the rotating auger with the desired torque and rotation speed.

3. FABRICATION AND TESTING

The test setup and drill components were fabricated using internal machining facilities or purchased if available. The drill bit body was made from aluminum and the impact parts, like the crown and impact ring, from hardened steel. The crown cutting teeth were made out of tungsten carbide and brazed onto the crown. The drill bit is mounted inside two bearings that allow rotation while maintaining axial alignment and between two wave springs that allow a limited axial motion (Figure 6, left).

The motor and gearhead with the desired specifications were selected and purchased to provide the rotating auger with the desired torque and rotation speed. Two additional gears transmit the rotation from the motor shaft to the drill bit. The piezoelectric actuator has a stack of 2" diameter piezoelectric ceramic and a resonance frequency of 5.25kHz. The preload between the piezoelectric actuator and free mass is 80N and includes the compression of the preload spring and the actuator weight. A number of different free masses were designed and fabricated ranging from disk to torus shape and having 150g to 350g mass (Figure 6, right).

Figure 5 The assembled drill and test setup

Figure 6 Drill bit motor mounting (left) and free masses (right)

It is critical that the Auto-Gopher's performance under various drill parameters be determined. Specifically, it was desired to observe how the percussive motion improves drill penetration rate when coupled with rotary motion.

Many parameters may affect the performance of the drill. These parameters include the drive voltage, percent duty cycle, weight on bit, piezoelectric actuator preload, rock material, drive frequency, bit rotation speed…etc. The drive voltage is determined from the voltage input from a function generator to the piezoelectric actuator via a power amplifier. Previous testing has shown that excess heat generation may reduce drill performance, hence it was suggested that drilling intermittently in duty cycles may improve the drill rate by maintaining the piezoelectric actuator performance in the optimal parameters range. The percent duty cycle represents the ratio of the time during which the piezoelectric actuator is activated to the time between two consecutive activation series. For instance, given a percussive hammering "ON" time of five seconds, a 20% duty cycle would indicate that over a drill period of 25 seconds, the ultrasonic transducer is switched on for 5 seconds and off for 20 seconds. Tests have been performed with various drive voltage and percent duty cycle combinations at different weight on bit (WoB) values, and the time needed for the drill to reach 0.5 inches of depth was recorded in seconds. The weight on bit is the force between the bit and the rock and consists of the weight of the drill bit, the rotary drive system, the ultrasonic transducer and its housing, as well as the rest of the testing assembly components. Because the weight of the moving system was larger than the desired WoB part of its weight was unloaded by hanging various masses over a pulley (Figure 5). Further testing was also run to determine the drill performance using different free mass configurations and drilling at greater depth.

The parameters investigated in this case were the drive voltage, percent duty cycle, and the weight on bit. The goal attempted was to determine the optimal parameter combination. The drill parameters are shown in Table 1. Tests were performed at 0.4V, 0.55V, and 0.7V of drive voltage, 20% and 40% duty cycle, and approximately 4kgf, 5kgf, 6kgf, 7kgf, and 8kgf of weight on bit values. A harder limestone was chosen as the rock material, and the drill tests were performed to a depth of 0.5 inches. During these tests, the rotation speed of the bit was kept constant at approximately 70RPM. The results are plotted below in Fig. 7, Fig. 8, and Fig. 9.

Table 1 Optimal test drill parameters

Bit Rotation Speed (RPM)	70
Drive Voltage (V)	0.4, 0.55, 0.7
Duty Cycle (%)	20, 40, 60
Transducer Preload (N)	~50
Weight on Bit (kgf)	~4, 5, 6, 7, 8
Drill Depth (in)	0.5

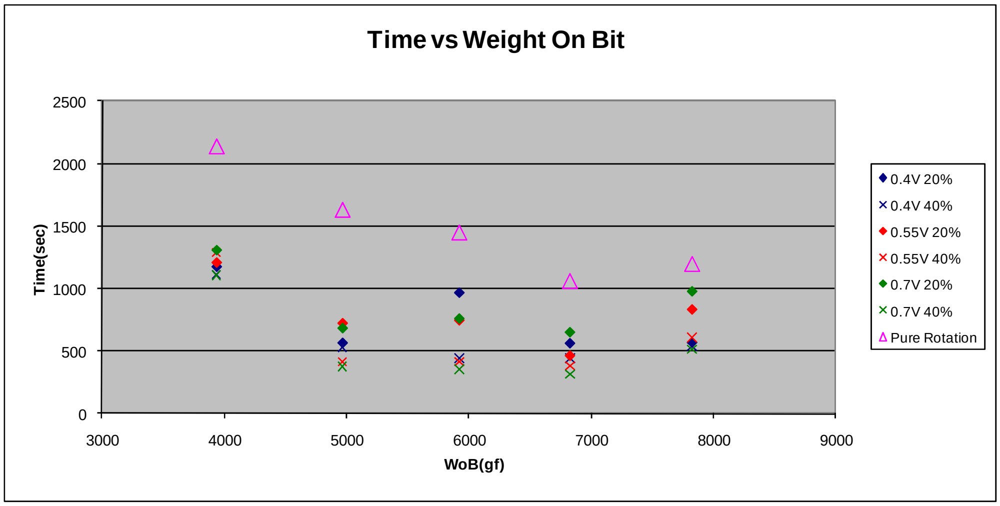

Figure 7 Drilling time

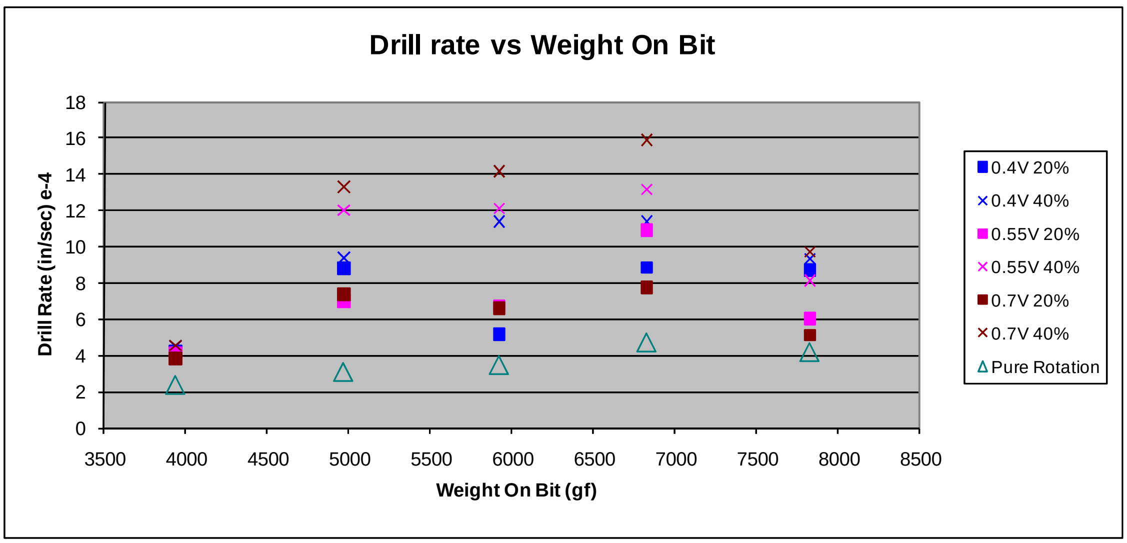

Figure 8 Drilling rate

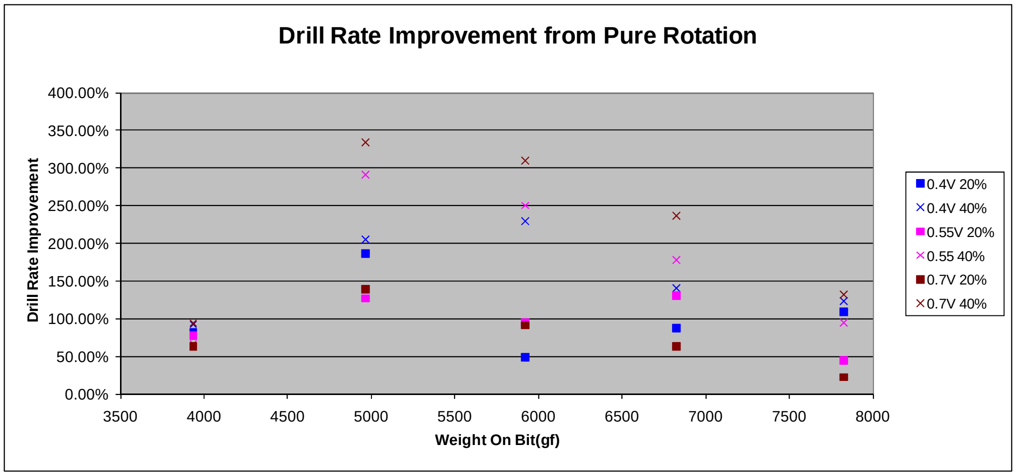

Figure 9 Drill rate improvement

The results above indicate that the optimal values for weight on bit are approximately in the 5-7kgf range. The plots also suggest that drilling at 40% duty cycle may be a decent compromise between having enough percussive hammering time and maintaining a desirable actuator temperature. The data also shows that 0.7V of drive voltage provides the highest drill rates at the current drill depth, though this may or may not be feasible depending on the power limitations. Finally, the data indicates a significant amount of improvement from drilling with pure rotation to drilling with rotary-percussive motion, with the maximum improvement being as large as 334%.
The tests shown above were performed with a fixed rotation speed of approximately 70 RPM at the bit and adding percussive hammering on top. Though the addition of percussive hammering vastly improves drill rate, one could argue that it is simply the result of the additional power spent on drilling. In this case, we would want to know whether the drill rate would differ between having 90W of rotation power and having 90W of rotary percussion. The detailed parameters of the two cases are tabulated below:

Table 2 Pure rotation drilling parameters

Motor Power (W)	~90
Rotation Speed (RPM)	245-277
Motor Voltage (V)	48
Motor Current (A)	~1.9
Drive Voltage(V)	N/A
Duty Cycle (%)	N/A
Actuator Power (W)	N/A
Transducer Preload (N)	~50

Table 3 Rotary percussive drilling parameters

Motor Power (W)	~53
Rotation Speed (RPM)	70-104
Motor Voltage (V)	48
Motor Current (A)	~1.1
Drive Voltage(V)	0.6
Duty Cycle (%)	20
Actuator Power (W)	~36
Transducer Preload (N)	~50

Five trials of each were performed and the results are shown in Fig. 10 with the blue points denoting pure rotation and red points denoting rotary percussion. The average drill rate is $8.60e^{-4}$ in/sec for pure rotation, and $10.14e^{-4}$ in/sec for rotary percussion. Though rotary percussion provides a slightly higher average drill rate, the difference is not extremely impressive, and the performance is somewhat inconsistent. One possible explanation may be that for softer rocks (such as limestone, the sample for the tests above), percussive hammering might not provide a substantial difference to the drill performance. Other parameters that may have affected the consistency of the results include the difference in hardness across the limestone surface, and heat generated by the actuator. An additional source of inconsistency may also exist due to the method via which the power was read and kept constant. Specifically, attempts to keep the motor power constant were made by visually monitoring and adjusting the current input such that the approximate average remained at either 1.9A (pure rotation) or 1.1A (rotary percussion) while providing a constant voltage. However, this method is rather crude and cannot guarantee a high degree of accuracy, since the current readings usually vary by quite a bit. Similarly, the power input to the piezoelectric actuator was monitored via the power meter of a Labview VI written program, which may also vary from time to time.

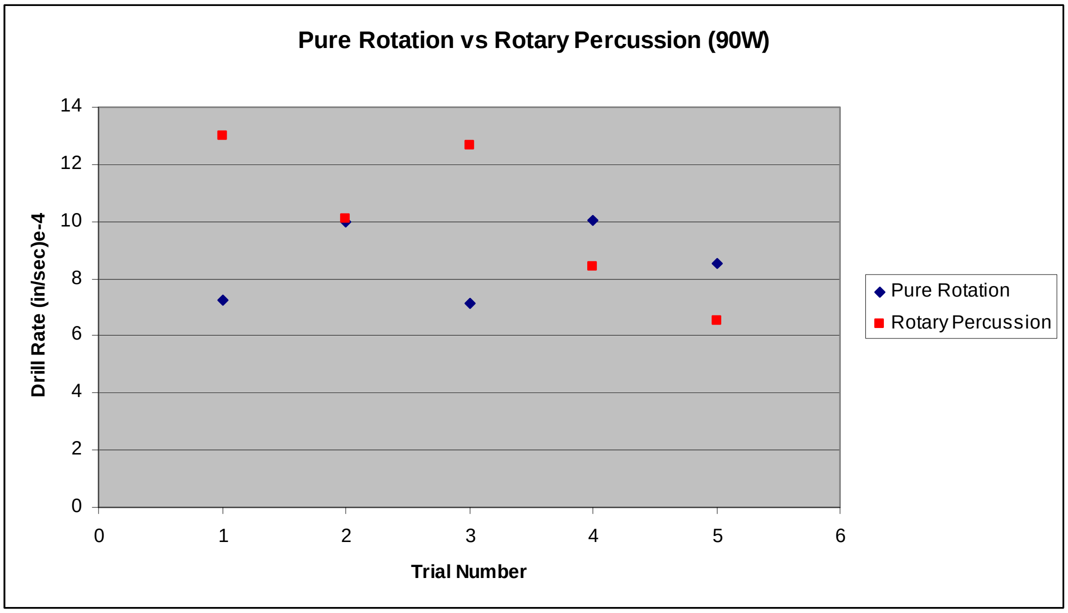

Figure 10 Rotation vs rotary-hammer drilling comparison

4. CONCLUSIONS AND FUTURE WORK

Drill tests were run to determine how the drill rate would vary with different settings and drill parameters. First a softer limestone was chosen as the sample, and tests were run with different drive voltage and duty cycle combinations as well as with pure rotation by the motor. Though a slight difference was observed between drilling with pure rotation and rotary percussion, the difference was not significant and no identifiable patterns could be deduced. A harder limestone was chosen afterwards for testing and the results indicate a range of desirable weight on bit values as well as the optimal duty cycle percentage. In addition, the results have suggested that vast improvements were achievable by drilling with rotary-percussive hammering compared to drilling with pure rotation, and the maximum improvement in the data was as high as 334%. This suggests that percussive hammering provides more improvement in the drill rate on harder rock materials. A couple tests were also run to a depth of 2 inches to observe the drill's performance when drilling to slightly greater depths. The results show that the drill has no problem drilling to greater depths, and place the average drill time at about 35 minutes.

It was also desired to verify the difference between drilling by pure rotation and by rotary percussion while keeping the overall power constant. Tests were performed separately having 90W of power input to only the motor in one case, and having rotary-percussive drilling with 90W combined. It was observed that rotary-percussion would provide a higher drill rate on average, though the performance was quite inconsistent. Since the previous drills were performed with the slightly "edgier" 230g free mass, the impact of different free mass geometries was then investigated by running the same test with a 150g and 250g free mass that took a rounder donut shape. The results suggest that the 150g free mass performed the best, drilling 0.5 inches in an average of 408 seconds. It was also observed that the round free masses performed more consistently than the 230g mass.

Previous studies have suggested that heat and loading may shift the resonant frequency of the ultrasonic transducer, and the drill penetration rate may be reduced when the transducer is not operating in resonance. Existing software developed for the USDC was utilized to search for the resonant frequency using electrical admittance as criterion, and shift the drive frequency accordingly. An alternative method was developed by using the average power input as the criterion instead, and was also able to successfully track the resonant frequency with the same hill climbing algorithm.

Future tests may include exploring additional drill parameters. Different rock surfaces can be chosen based on material hardness, and free masses with different configurations can be tested to determine the optimal geometry. In addition, current tests data were mostly obtained at 0.5-inch drill depths. Future drill tests may involve drilling at greater depths and observing the corresponding performance. The cuttings-removal mechanism may also be investigated. By drilling at more than one full core depth, one may determine whether or not the flutes are able to sufficiently transfer the cuttings to the windows and prevent the cuttings from interfering with the drill. Finally, this report presents two methods of resonant frequency tracking. Future tests may be performed to determine under which situations one method might be more advantageous than the other.

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