

Testing and Development of a Percussive Augmenter for Rotary Drills

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Hammering drills are effective in fracturing the drilled medium while rotary drills remove cuttings. The combination provides a highly effective penetration mechanism. Piezoelectric actuators were integrated into an adapter to produce ultrasonic percussion; augmenting rotary drilling. The drill is capable of operating at low power, low applied force and, with proper tuning, low noise. These characteristics are of great interest for future NASA missions and the construction/remodeling industry. The developed augmenter connects a commercially available drill and bit and was tested to demonstrate its capability. Input power to the drill was read using a multi-meter and the augmenter received a separate input voltage. The drive frequency of the piezoelectric actuator was controlled by a hill climb algorithm that optimizes and records average power usage to operate the drill at resonating frequency. Testing the rotary drill and augmenter across a range of combinations with total power constant at 160 Watts has shown results in concrete and limestone samples that are as good as or better than the commercial drill. The drill rate was increased 1.5 to over 10 times when compared to rotation alone.

I. Introduction

Percussion and rotation have long been the methods of penetrating materials. Percussion is very effective at fracturing hard, brittle materials like stone and ceramics. Rotation is more effective on soft and/or ductile materials such as wood, plastics, and metals. One advantage of rotation is the removal of cuttings from the hole. Percussion fractures the material, but continues to hammer at the loose material in the hole unless it is removed. This wastes energy that could go into penetrating the medium. Combining rotation and percussion produces a highly effective penetration mechanism. Existing hammer-drills produce their hammering mechanically. A novel rotary drill augmenter was developed by JPL's Advanced Technology Group and tested in this study⁶. The device uses piezoelectric actuators to augment any rotary drill with percussion. Piezoelectric materials produce a voltage when under an applied stress. The inverse is also true; an applied voltage produces mechanical stress and deformation in the material. By applying a sinusoidal voltage at ultrasonic frequency the piezoelectric material rapidly expands and contracts, which creates hammering. A LabViewTM and MATLABTM program controls the drive frequency of the augmenter using a hill climb algorithm. Rotation and percussion power supplies

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are separate allowing different power combinations to test numerous cases and determine the benefit of the augments over only rotation.

There are many potential advantages to using piezoelectric actuators to create hammering^{4,5}. They operate under low power. The actual tip displacement is very small so it is not felt by the user. They do not require high axial loading to penetrate materials, making them very easy to use. Low power and low applied force are desirable traits for sample acquisition in planetary exploratory missions with very tight power budgets. The ease of use and quieter operation (compared to other hammer drills) are also traits that interest the construction and remodeling industry and the tested augments was developed as a prototype for technology transfer to this industry.

II. The Augments

A. Structure

The augments was designed to provide hammering to any commercial rotary drill. It fits between the drill and the bit. The bit is inserted into the adapter and the casing connects through the slip ring to fit the three point chuck of the drill, see Figure 1. This allows the augments to be used with many rotary drills.

The augments is driven by a piezoelectric stack and is constructed of a backing, an amplifying horn, an adapter piece, and a slip ring. A mounting flange is on the horn and connects to a casing that fits a commercial drill's three point chuck. A bolt from the backing to the horn maintains the piezoelectric stack in compression, which is needed since piezoelectric ceramics are very weak in tension. The stack consists of 6 piezoelectric rings layered with electrodes to supply power. The horn diameter tapers from the ring diameter to amplify the displacement at the tip⁴. The length of the adapter is determined through modal analysis (see section II. D) to minimize deflection at the mounting plane. A slip ring is used to transfer power from stationary to rotating components.

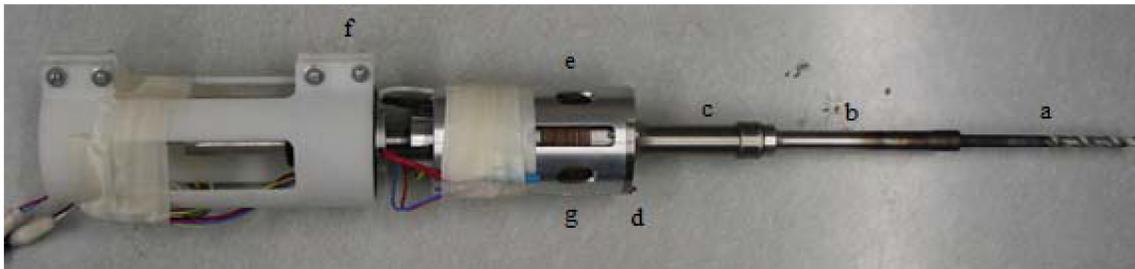


Figure 1. The Augments consists of (a) bit, (b) adapter, (c) horn, (d) mounting plane, (e) casing, (f) slip ring, (g) piezoelectric stack inside of casing.

B. Drive Frequency Control Program

The augments is most effective when run at resonate frequency. This produces the largest tip displacement and results in more energy being imparted to the drilling medium. The control program is needed because resonating frequency is not completely stable. It will shift with temperature, changes in the applied force, contact with the side of the hole being drilled, and imperfect electrical transmission through the slip ring. To create a list of constant drive frequencies to apply at every possible case would be inefficient and not effective.

The basic algorithm was available from previous interns and the Ultrasonic/Sonic Driller/Correr (USDC) work already completed by JPL's Advanced Technologies Group. Initial testing was done without adjusting the program and it was found that the older program was unable to deal with the instability. It could not reliably find and maintain resonate frequency.

The program works by reading the current and voltage and comparing magnitudes to that of the previous step to either increase or decrease drive frequency. Initially it only obtained the peak value to decide the next frequency and stepped by 4 Hz. The problem is that current and voltage become out of phase when the drill is not at resonance, so the peak values are not occurring at the same time. The small frequency step was another problem; due to the instability in the signal the small step size led to shifts based on noise.

The program was adjusted to calculate power used by the augments. It logged simultaneous arrays of voltage and current, multiplied them element by element, and averaged by the length of the array. The length of the array is determined by the drive frequency to contain a set number of whole periods. Power is a better value to optimize and is important test data. The step size was increased to 20 Hz. The larger step size quickly approaches resonance, but oscillates above and below it. The program monitors past frequencies to recognize this pattern and reduce the step size when needed. Power values are also monitored and the step size will increase if there is a significant sustained drop. The ability to log test data in a text file was also added.

C. Testing

All testing was conducted following the same procedure. The load was measured on a scale before and after testing. The drill was turned on and desired rotation power was set by a manual control. Input voltage and other controls of the drive program were prepared. The program was started, the drill is lowered onto the sample and a timer started when it contacts the sample. Tests were run for two minutes, or stopped when the hole depth exceeded the fluted length of the bit. A tachometer was used to measure rotation speed. Power, current, and voltage to the drill were read from the multi-meter. The text file created by the drive program was used to determine power use and other data for the augments. Two types of tests were completed; constant rotary power and constant total power.

Constant rotary power tests were conducted with 50 W of power to the commercial drill used to provide rotation. The input voltage to the augments was raised from test to test to determine the effect of increasing percussive power. Testing was done at a preload of 4.2 kgf (weight of drill and augments) and repeated at 7.0 kgf. These tests were conducted on limestone.

Constant total power tests compared the augments to rotation on more equal terms. The power to each was controlled to use a total of 160 watts at varying combinations. This test shows the benefit of allocating some power to hammering. Testing was done on soft concrete and limestone at a preload of 4.2 kgf (weight of drill and augments) and repeated on limestone at 7.0 kgf. The hammer-drill setting on the drill being used was also tested at 160 watts on the same samples under the same loading.

D. Modal Analysis

Operation at resonate frequency creates a deflection wave through the augments and bit. A whole wavelength exists along its length resulting in two locations that undergo no axial deflection. The mounting plane is positioned at one of these nodes to reduce stress and isolate the hammering from the rest of the drill. Finite Element analyses, using ANSYS Multiphysics™, were used to design a future 2 inch diameter coring bit model^{1,2} (Figure 2) An iterative process of adjusting component length above or below the mounting plane is used to bring the nodal and

mounting planes together. Adjusting the length of adapter and backing will move the nodal plane by shortening the deflection wave, as shown in Table 1.

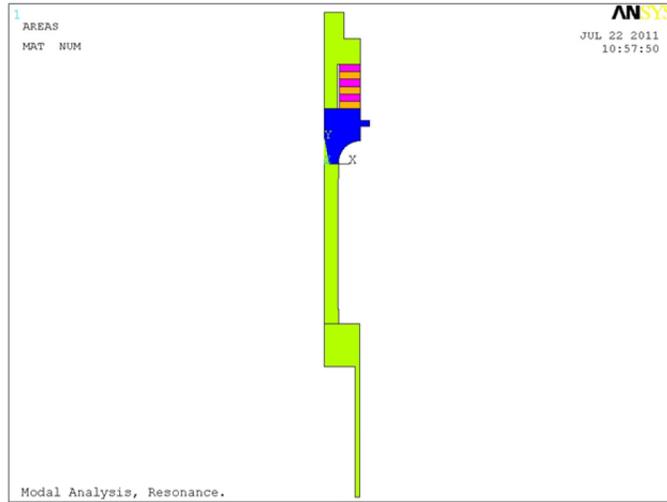


Figure 2. ANSYS™ Model of 2 inch Corer Model.

Table 1. Modal Analysis Iterations to Align Mounting and Nodal Planes

	Nodal Plane is	Displacement	Adapter Length	Backing Length	Mounting Ring offset
Freq	_____ flange	mm	mm	mm	mm
12937	below	6.20E-03	92.28	18	10
12931	below	1.37E-04	92.28	19	10
12926	above	-5.92E-03	92.28	20	10
12976	below	4.85E-03	90.28	18	10
12976	below	4.53E-03	90.28	18	9.9
12975	below	3.65E-03	90.28	18.2	10
12974	below	2.45E-03	90.28	18.4	10
12935	below	3.78E-03	92.28	18.4	10
12952	below	5.88E-04	92.28	18.4	9
12952	within	-1.60E-03	92.28	18.4	8

The augments must be tuned to operate with a specific bit. To allow multiple bits to be used with a single augments the backing and horn were held constant while a separate adapter was tuned to each bit. The goal is a series of tuned adapters and bits that can all be used on the same horn. Multiple bit choices are important to sampling missions as well as construction applications.

III. Test Results

The tests show that the augments greatly increases drill rate over rotation. Due to differences in drill times, all comparisons and graphs are of drill rate. All of the test data are based on the maximum power drawn by the augments during the test. The average power used for the whole test is much lower than the peak from an iteration of the frequency control program.

A. Constant Rotary Power

This test was used to determine the limits of the augments and find if drill rate would plateau or continue to grow. The results shown below in Figure 3 did not find a plateau, but a continued increase. An upper limit was determined due to excessive heat generated when operating the

augmenter at over 200 watts. The data also show that applied force on the drill has little effect on drill rate. The drill rates are more variable at higher power. One factor is the time the program takes to find resonance. If it takes 20 seconds to drill 3 cm at resonance, the difference of 2 to 6 seconds to find the frequency means a difference of 8.2 cm/min to 6.9 cm/min. This difference can be reduced by a better initial guess frequency. Another factor in this distribution is non-uniformity in the rock sample being drilled.

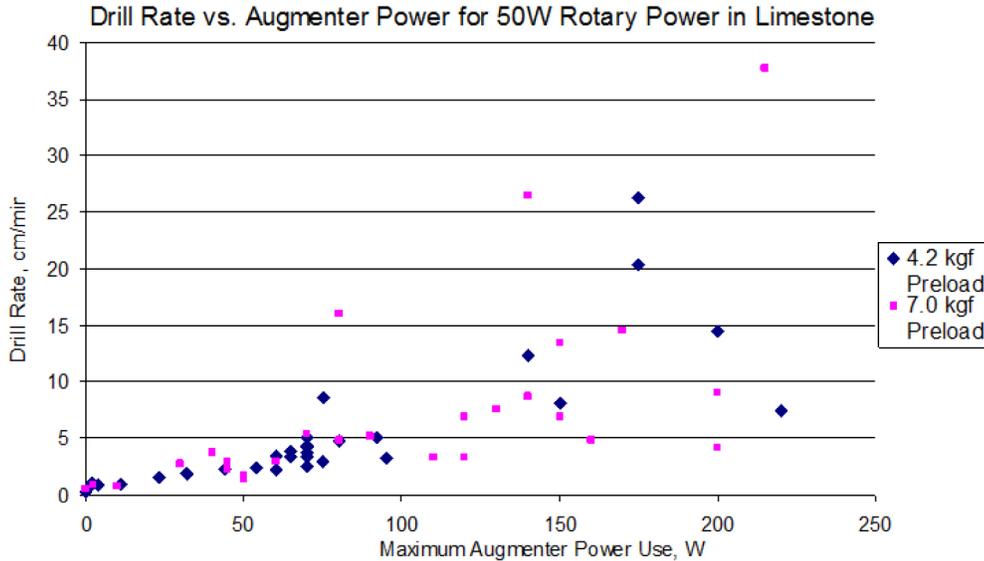


Figure 3. Constant Rotation Power Testing for both Load Cases.

One of the interesting results from this test was a small increase in rotation speed with augmenter power, despite a constant power. Higher power results in a larger displacement at the bit, which in turn reduces the resistance that the bit feels from the sample. This allows the drill to spin faster, approaching the free rotation speed. Higher load tests were attempted, but were beyond the stability of the test structure, and could not produce reliable results. Even the 7.0 kgf testing has some instability that may have affected drill rates.

B. Constant Total Power

The constant total power tests in limestone were very conclusive, see Figure 4. For the same amount of power the drill rate increased up to ten times. Drills rates made a slight rise with increased preload. The data also shows that the augmenter’s performance is comparable to the commercial rotary-hammer drill at 7.0 kgf, and several times faster at the lower load. There is a marginal increase in drill rates at high power for the higher load. The spread of drill rates is more extensive at all power levels than in the constant rotation power tests. Comparing drill rates and power levels between Figures 3 and 4 shows the benefits of much higher power use.

Figure 5 shows the results of constant total power tests in a softer concrete sample. The augmenter did not improve drill rates as drastically as in the limestone; only giving a threefold increase. There was also a decline in drill rate at higher augmenter power. This was due to low rotation power and high drill rates that allowed a buildup of material in the hole. With loose concrete in the hole, the hammering did not impart its full power to the rock. The softer material

was part of the difference, as it crumbled away much faster than the limestone. The commercial rotary-hammer drill and augmenter performed at comparable rates again.

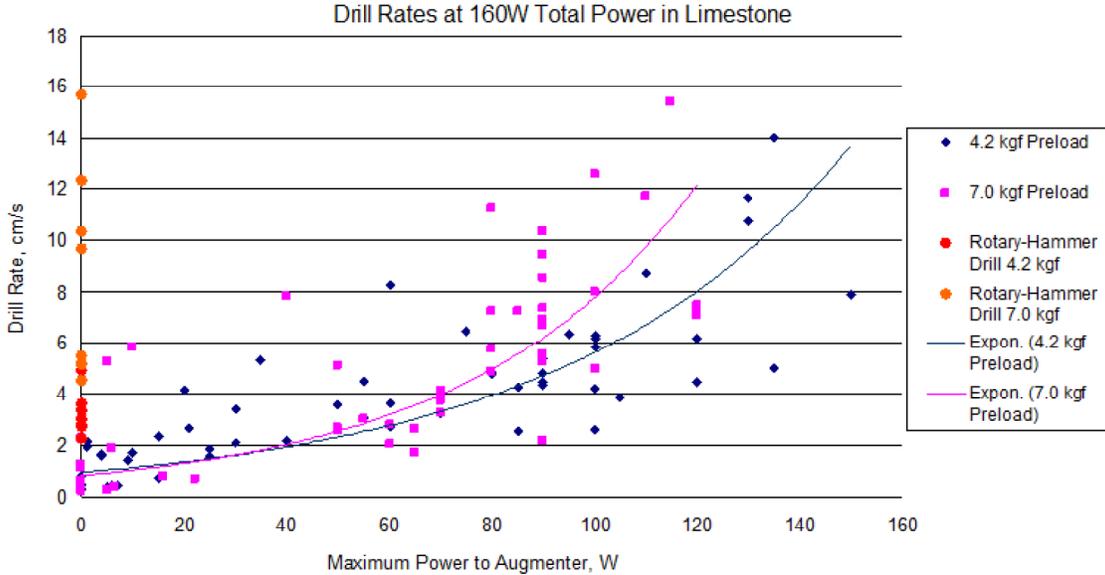


Figure 4. Constant Total Power Results in Limestone

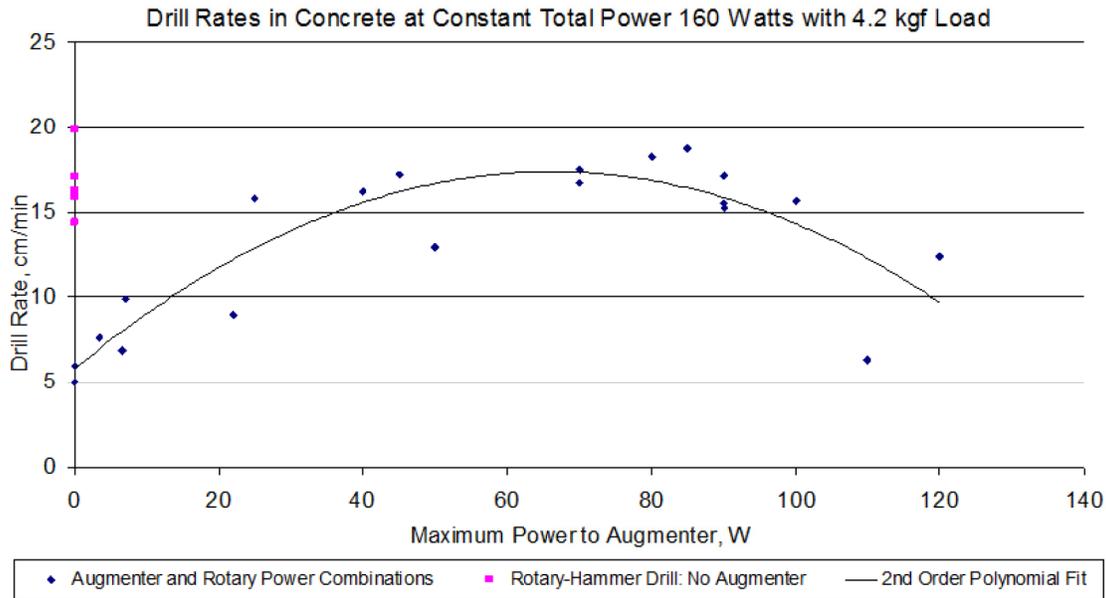


Figure 5. Constant Total Power Results in Concrete

IV. Conclusion

Piezoelectric actuators provide a great mechanism for percussion and, when combined with rotation, penetration. Drill rates increased several times in all samples compared to rotation alone, and tied or exceeded the drill rate of the commercial rotary-hammer drill. The reaction forces on the user are significantly reduced compared to mechanically driven commercial rotary-hammer drills. Increased loading did not have an appreciable effect on the augmented drill rate, but further testing on a more stable platform may contradict this. For the coring model being

developed the stability of the test rig should be of utmost importance, as well as the rotational symmetry of the augments. The model used in these tests was slightly off center, adding to the shaking allowed by the vertical slide.

The drive program can also be improved. The largest problem is an unpredictable five second lag where it reads zero voltage. The source of this error is unknown and may be due to background operations on the computer running the program. Other possible improvements are to optimize the criteria of when to change step size and to log the frequency at peak power and return to that frequency if it is caught on at a small false resonance peak. Averaging power use could also be added. Varying the load during a test would simulate the inconsistent force of a person operating the drill. It would also be a good test to see how robust the control program is. Duty cycling is another potential addition. Duty cycle would reduce power use even more. It could be more effective to run duty cycle at high power than to run a constant lower power. To reduce the time to find resonating frequency the initial drive frequency could be scaled to the input voltage instead of entered manually. The majority of testing used the same initial frequency, but a slightly more tailored approach could increase drill rates.

One of the interesting possibilities of piezoelectric percussive drilling is that the holes do not need to be round. The augments was constrained to creating round holes because it used rotation as a cutting removal mechanism. If other removal methods are developed, holes of nearly any shape could be made at high penetration rates. Of particular interest for construction applications are rectangular holes for HVAC ducting.

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