Actuation Using Piezoelectric Materials: Application in Augmenters, Energy Harvesters, and Motors

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ABSTRACT

Piezoelectric actuators are used in many manipulation, movement, and mobility applications as well as transducers and sensors. When used at the resonance frequencies of the piezoelectric stack, the actuator performs at its maximum actuation capability. In this Space Grant internship, three applications of piezoelectric actuators were investigated including hammering augmenters of rotary drills, energy harvesters, and piezo-motors. The augmenter shows improved drill performance over rotation only. The energy harvesters rely on moving fluid to convert mechanical energy into electrical power. Specific designs allow the harvesters more freedom to move, which creates more power. The motor uses the linear movement of the actuator with a horn applied to the side of a rotor to create rotational motion. Friction inhibits this motion and is to be minimized for best performance. Tests and measurements were made during this internship to determine the requirements for optimal performance of the studied mechanisms and devices.

1. INTRODUCTION

One aspect of space exploration includes the search for life on other planetary bodies such as Mars, the moons of Jupiter, or others. Surface and subsurface samples may be analyzed in-situ or returned to Earth for extensive analysis. Planetary drilling is a challenge particularly for extended depth, which would be needed to reach beyond the weathered layer, and on Mars, the depth can be over two meters. To address the need for samplers, the scientists at the JPL's NDEAA Lab are developing various mechanisms that are driven by piezoelectric actuators and using the results to benefit the industry in the form of technology transfer. This includes a deep penetrator that is a wireline rotary-hammering drill with the hammering produced by a USDC (ultrasonic/sonic driller/corer)-based mechanism actuated by a piezoelectric stack. The drill is called Auto-Gopher, and it is a relatively low-mass mechanism equipped with a low holding torque anchor [1-4]. One other mechanism that benefited from innovation resulting from this development is a piezo-motor that uses the vibrations of piezoelectric stacks and a side-pushing set of horns to turn a rotor [5].

The objective of this summer project is to work on piezoelectric-actuated mechanisms. One type of piezoelectric actuator is the stack, which is a collection of piezoelectric plates connected mechanically in series and electrically in parallel. When used at the fundamental resonance frequency of the piezoelectric stack, the actuator displacement is maximal. These include the following three tasks: (a) hammering augmenter for a rotary drill, (b) energy harvesters, and (c) piezo-motors. The work time this summer has been divided amongst these tasks.

The drill augmenter task includes testing drive parameters and drill bits for the best combination of frequency and voltage input with duty cycling in order to maximize the drill rate. There have been two other drill bits tested by the lab. Their resonance frequencies were found using an impedance analyzer. When the drill operates at the resonance frequency of the piezoelectric actuator and the drill bit, the combination of percussion and rotation improves the drilling rate. While past tests may have been operated at the resonance frequencies, there was considerable instability with the test stand and a design improvement was needed.

The energy harvesting task uses flow over a piezoelectric actuator to create power. The mechanical energy of the fluid as it passes over the actuator is changed to electrical power. The energy harvesters rely on the converse piezoelectric effect, which produces an electric field when stressed by a moving fluid. The piezoelectric converts mechanical energy into electrical energy and when this is done at a given frequency, electrical power can be generated. Specific designs allow the flow to produce more force on the harvesters and move the tip of the piezoelectric bimorph more, which creates more power. To avoid compromising the potential patentability of the related invention, no further details of this task are provided in this report.

The final task focuses on turning linear vibration of piezoelectric horns into rotational motion. The lab has done some work previous to this summer, but friction has hindered optimal torques and rotational speeds from the motor. Improving the freedom of motion will allow for these performance criteria to be met.

2. DRILL AUGMENTER

A. Background

A commercially available Hilti drill was reconfigured and fitted with an adaptor to contain a piezoelectric transducer in line with the drill bit as shown in Figure 1.

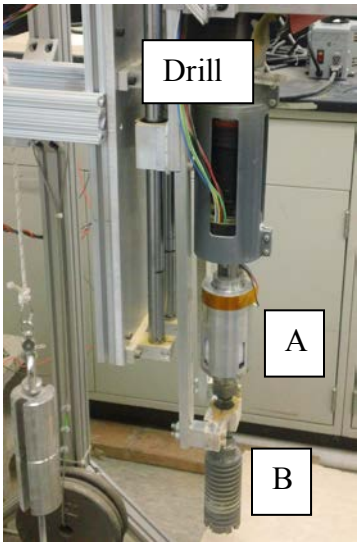

Figure 1. The Hilti drill with the transducer (A) and the drill bit (B).

This setup was built previous to this summer. The transducer is made from a stack of two-inch diameter disks of PZT ceramic material that is kept in compression so it will not break during the voltage cycling. Performance tests were conducted at different power levels to the transducer and drill motor over a range of frequencies for best drilling performance into limestone,

B. Procedure

1. Testing on a Rotation Basis

Testing of the drill bits begins with a reading from an impedance analyzer to have a rough estimate of the resonance frequency. An example is presented in Figure 1.

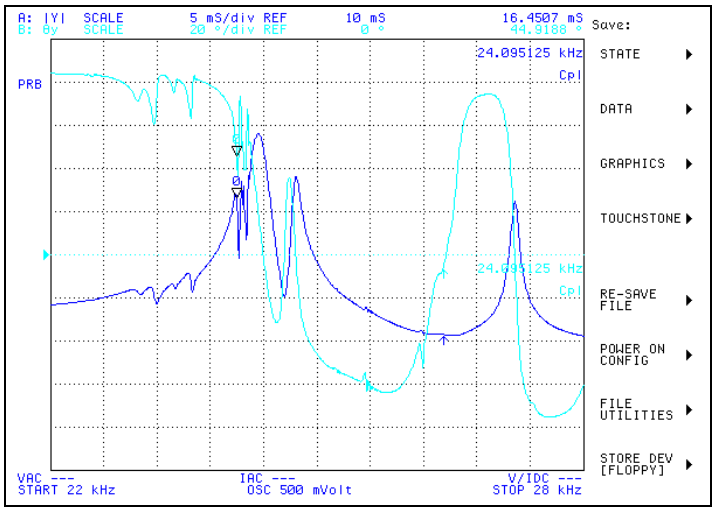

Figure 2. Impedance spectra of the transducer attached to a rebar cutting bit.

For this bit, resonance is possible at 24.0, 24.2 and 24.4 kHz, and 27.6 kHz as indicated by the peaks along Channel A (dark blue). As the piezoelectric transducers are operated, the temperature and the boundary conditions change their resonant frequency. A computer program was previously developed by the NDEAA Lab scientists [6] (called "HillClimb" within a LabVIEW interface) to control the transducer drive frequency. The program starts with a user-defined drive signal frequency and seeks to increase the current drawn by the transducer for a specified voltage level. The function generator and oscilloscope send and receive data through the program's internal feedback loop. Based on this feedback, if a step change in frequency in one direction improves the electrical admittance, the steps continue in the same direction. If not, a step change occurs in the opposite direction. An amplifier enhances the signal from the function generator being sent to the ultrasonic transducer. Visual setup of the experiments is included within appendix A. The program essentially "maps" the frequencies where the drill's ultrasonic transducer would be most effective as observed by volumetric removal rates. Two tests are run at each frequency to ensure repeatability.

In order for a drill to be successful, a hole-start needs to be performed first. This hole-start consists of drilling only 2-3 mm deep or until the bit stabilizes, and dust particles will need to be vacuumed away and the measured start depth recorded. The ultrasonic transducer will then be turned on with settings determined by the specific test number. Set-up includes starting frequency, voltage input, duty cycle and type of washer (if used). The tests last for five minutes of rotation. A screen capture helps to record important information from each test. At the end of every test, measurements of depth reached, and inner and outer diameters of the drill site are taken. This allows for calculation of volume removed during the five-minute test period. Though depth is faster for analysis purposes, the volume removed is more accurate since the bit does not always grab the rock the same and may create a larger hole with side-to-side motion rather than add to drill depth.

Along with testing the capabilities of the ultrasonic transducer, a test with rotation only serves as the baseline for the tests with rotation plus percussion. The rotational speed is the same in either test for comparison purposes. All pertinent data are recorded, which includes the preload on the bit, and the power to the transducer and the drill.

2. Testing on a Power Basis

There is a second test that was performed for determining the transducer capabilities. This test measured the power distribution to both the transducer and the rotation. The power level to the transducer was set, and the rotation speed and preload of the drill were adjusted to reach a specified total power level (in this round of testing, 310 W was chosen). The use of duty cycling cut down the power to the transducer.

C. Results

Testing results so far have revealed up to 400% improvement of the drill performance with percussion in addition to the rotation. Testing began with the bolted coring bit, and the resonance frequency was comparable to previous data at 23.75 kHz with a voltage input of 0.35 V and a duty cycle of 100%. The rebar cutting bit also had similar improvement when percussion was added to rotation. The volume removed by the rebar bit is less than the coring bit; this has to do with the stability of the test stand. Though improved since the redesign, the coring bit does not grab the rock as well as the rebar bit, creating a larger cut due to the movement on the drill (and occasionally of the rock). Figure 2 shows the data taken to date for all configurations.

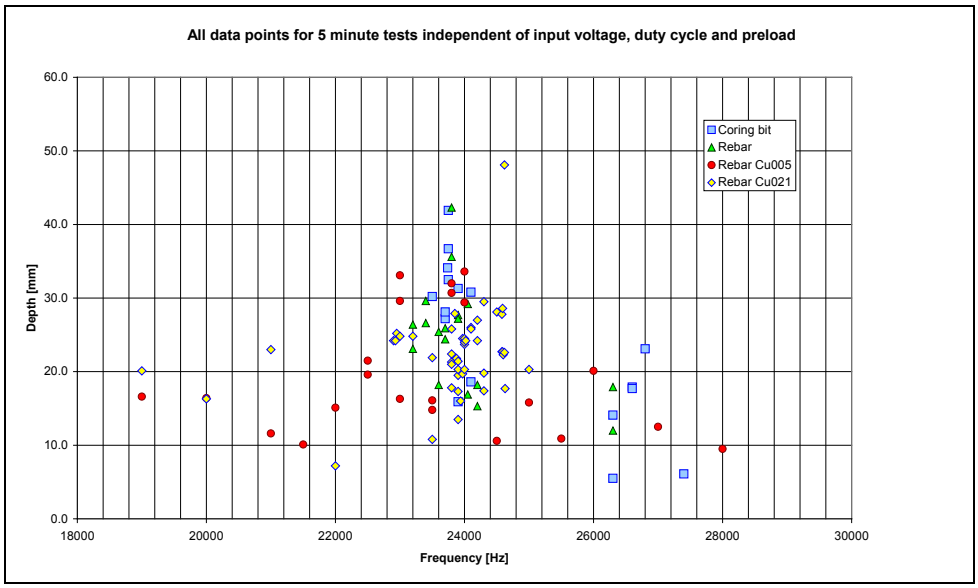

Figure 3. All data points taken to date.

After baselines were taken of each bit, washers were added to the rebar cutting bit to test the coupling between transducer horn and the adaptor as well as the adaptor and the drill bit. The data, as shown by Figure 3, are averaged for each resonance frequency present within the transducer for each configuration. For the rebar cutting bit with washers, the rotation only removal rate did not change, thus the use of two green symbols to match the green rotation line. The blue symbol matches the blue rotation line and likewise for the orange symbols and line.

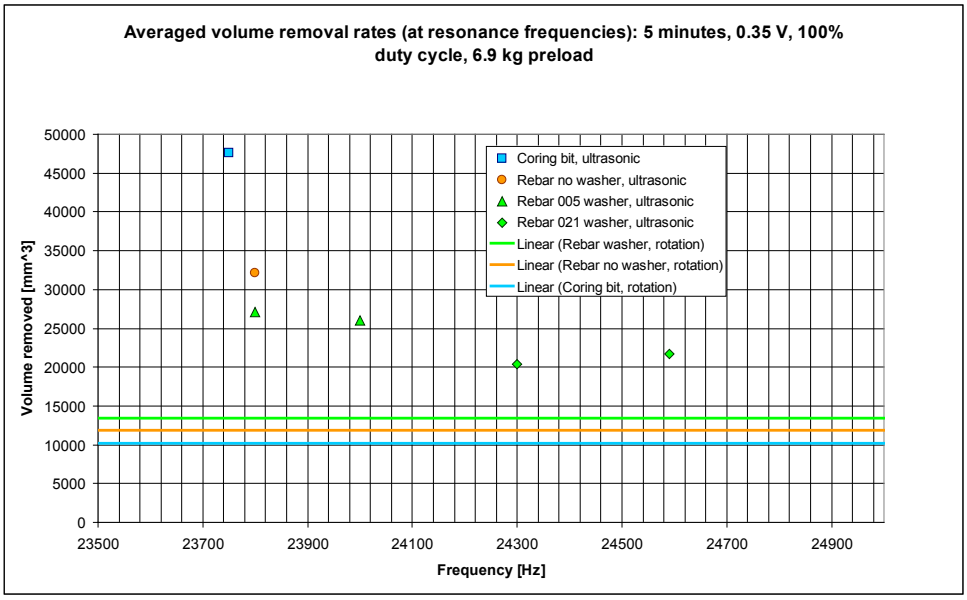

Figure 4. Averaged volume removal rates for data to date. Input voltage of 0.35 V at 100% duty cycle and 6.9 kg average weight on bit.

There is a slight disadvantage using washers than not using them as shown by the rebar cutting bit results. The washers may be damping the vibration produced by the transducer, thus reducing the drill's effectiveness. The resonance frequency for the drill with the bolted coring bit is approximately 23,750 Hz, and resonance frequency for the drill with the rebar cutting bit is 23,800 Hz with smaller resonances appearing at 24,000 Hz, 24,300 Hz and 24,600 Hz. There seems to be some temperature dependence in that when the transducer warms up, the resonance frequency drops.

The next phase of testing was to keep the total power the same for every test performed. This means the power is distributed between the transducer and the drill itself and stays constant between tests even if the input voltage or rotation speed changes. A power level of 310 W was selected for these tests, and the "HillClimb" program calculates what power the transducer gets from the selected input voltage. A duty cycle of 60% was chosen so the transducer would not overheat. Figure 4 shows the data where the power being sent to the transducer ranges from 0 to 100 W of the total power.

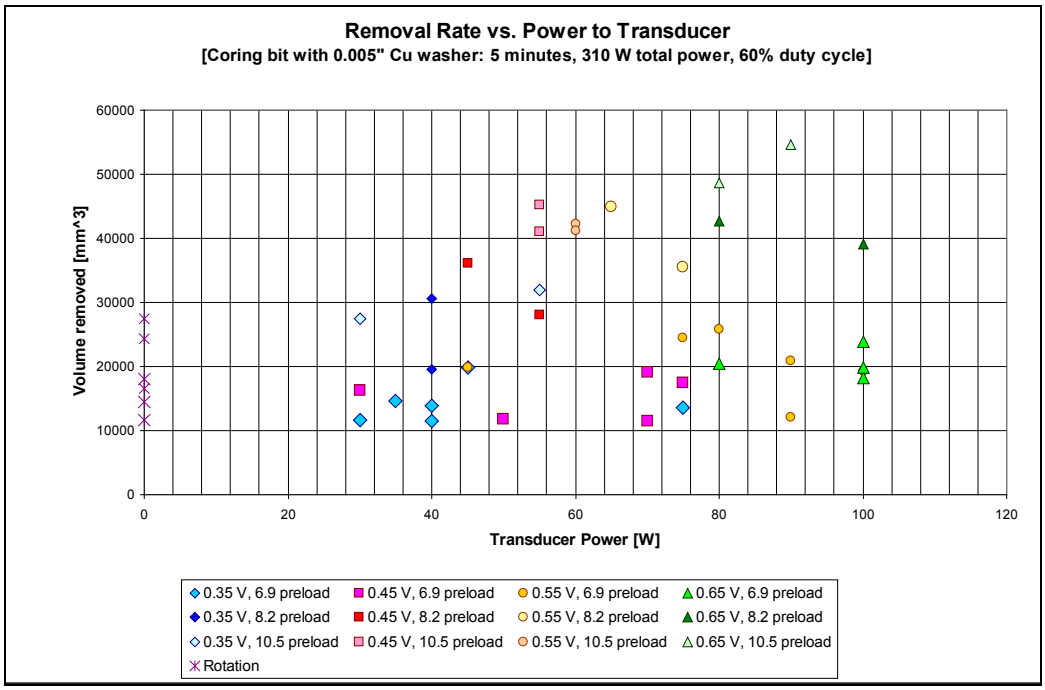

Figure 5. Removal rates for bolted coring bit with 0.005" copper washer and 310 W of total power.

The rotation only values are recorded as 0 W. The highest removal rate observed during testing was for 90 W transducer power at 10.5 kg weight on bit and an input driving voltage (before the amplifier) of 0.65 V. Further testing will incrementally increase the power to the transducer while decreasing the power to the drill rotation until the drill not is able to rotate the bit. Once completed, the test results will be analyzed for optimal drill performance along the varying power levels, input voltages and preloads.

The last portion of the test plan for the drill augmenter is to compare these results with a commercially available percussive drill. This future work will help to determine whether piezoelectric effects provided a benefit.

3. ENERGY HARVESTERS

A. Background

The piezoelectric energy harvesting consists of a mechanism for converting mechanical motion in a structure into electrical power. A new technology report has not been submitted at the time of this final report's deadline so this task is not discussed here. For the summer work, measuring the power generated as a function of the flow rates and the load resistance has completed characterization of harvester geometries. The experimental setup and a simplistic schematic of the test circuitry are shown in Figure 6.

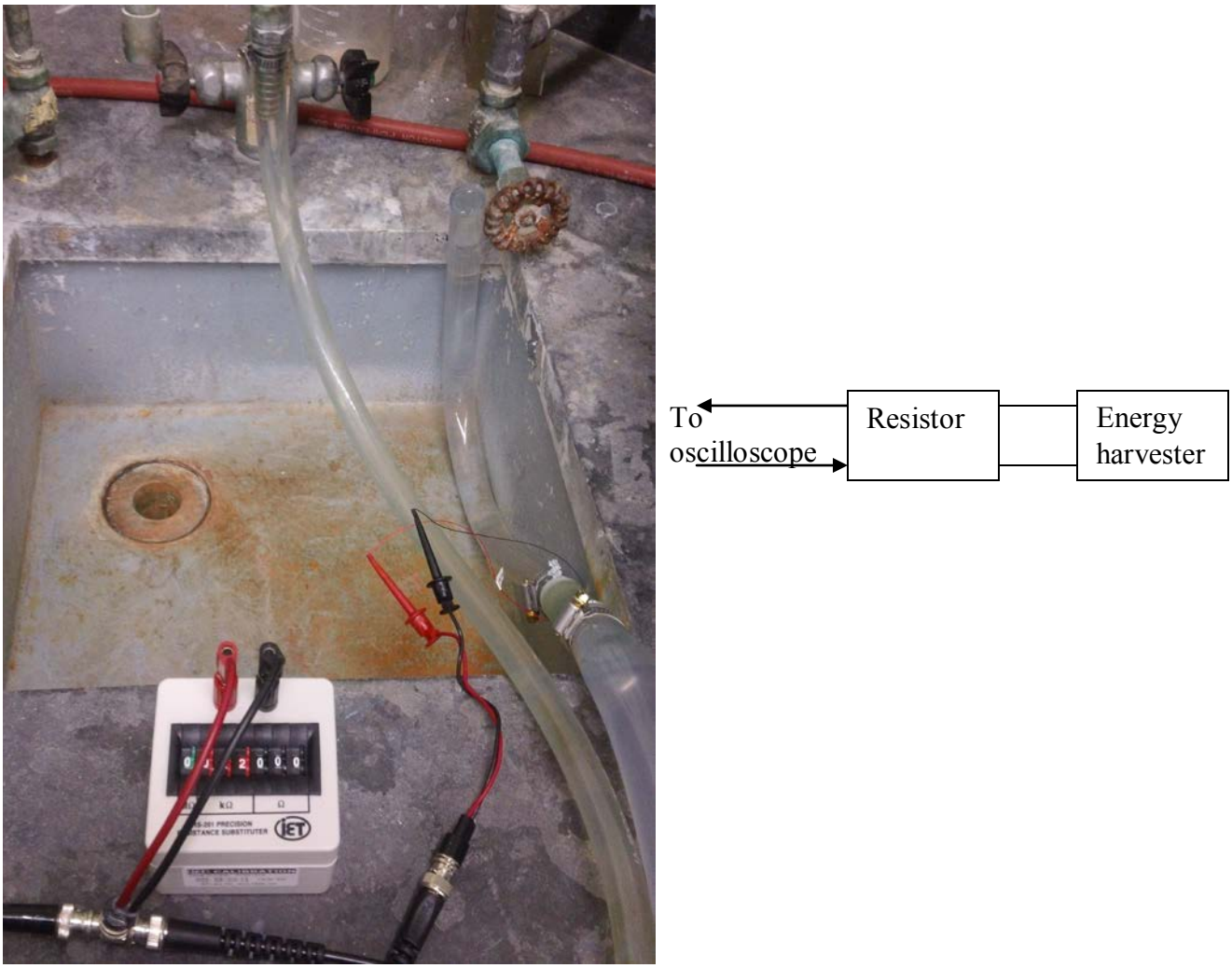

Figure 6. Test setup of energy harvesters, left, and circuit geometry, right.

An example of the data collected is shown in Figure 7.

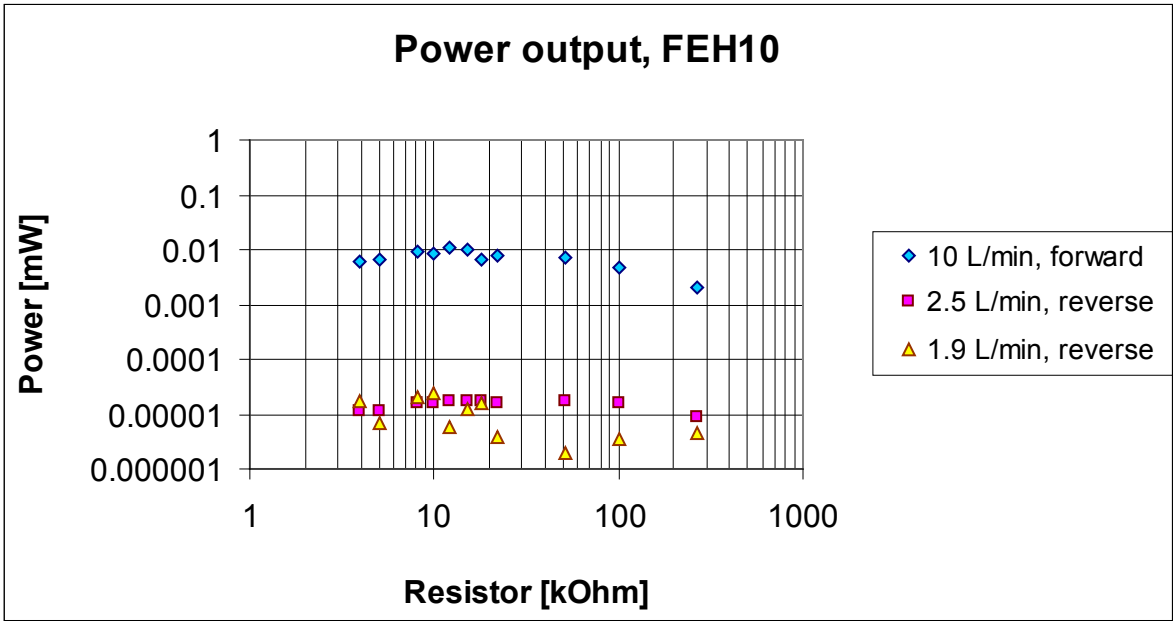

Figure 7. Power data collected from energy harvester.

4. PIEZO-MOTORS

A. Background

The study this summer focused on a piezo-motor that was developed at the JPL's NDEAA Lab. This motor is driven as a Barth type that is actuated by hammering a rotor from its side by several horn units. While a large configuration was demonstrated successfully, a miniature configuration that was produced is having difficulties. The problem is the result of excessive friction that is inhibiting the rotation. Current efforts are focused on addressing this issue.

B. Procedure

The piezo-motor works by horns pushing on the side of a rotor. These horns are manufactured into the motor frame and use 2mm-thick piezoelectric stacks to create mechanical motion. Impedance analysis for the miniature motor shows resonance bands at 170 kHz, 240-260 kHz, and 390 kHz. The setup is very similar to the setup described in Section 2 (also Appendix A) except the voltage input is much smaller.

C. Preliminary Results

The piezo-motor has not turned with a voltage and current input, but it does operate in the sonic range. This is an improvement compared to when the motor was last put together and no noise was produced.

5. FUTURE WORK

Future work includes comparing the drill performance to the performance of commercially available technology under the same conditions. The drilling performance of the Hilti rotary

drill augmented with the hammering from the piezoelectric actuated mechanism will be compared with the rotary-hammering capability of the Hilti and a DeWalt drill. This will show whether the piezoelectric actuated hammering makes improvement over current technologies in use.

For the piezo-motor that was developed, friction is still an area of concern. A way to relax the fittings but keep force on the rotor will need to be devised.

ACKNOWLEDGEMENTS

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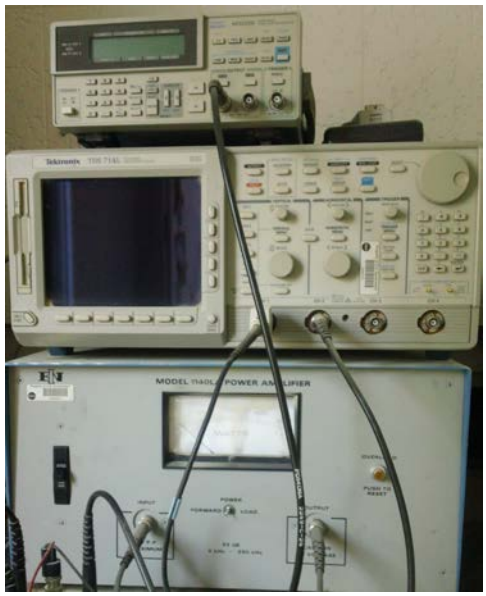
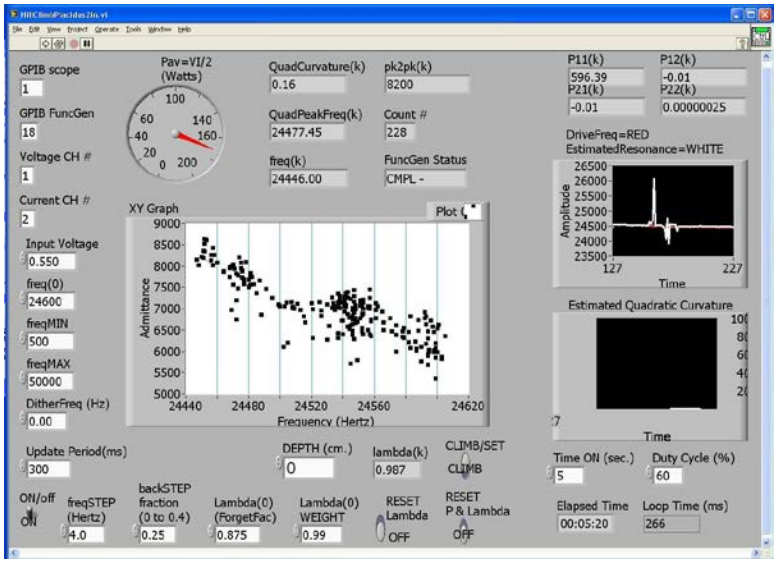
APPENDICES

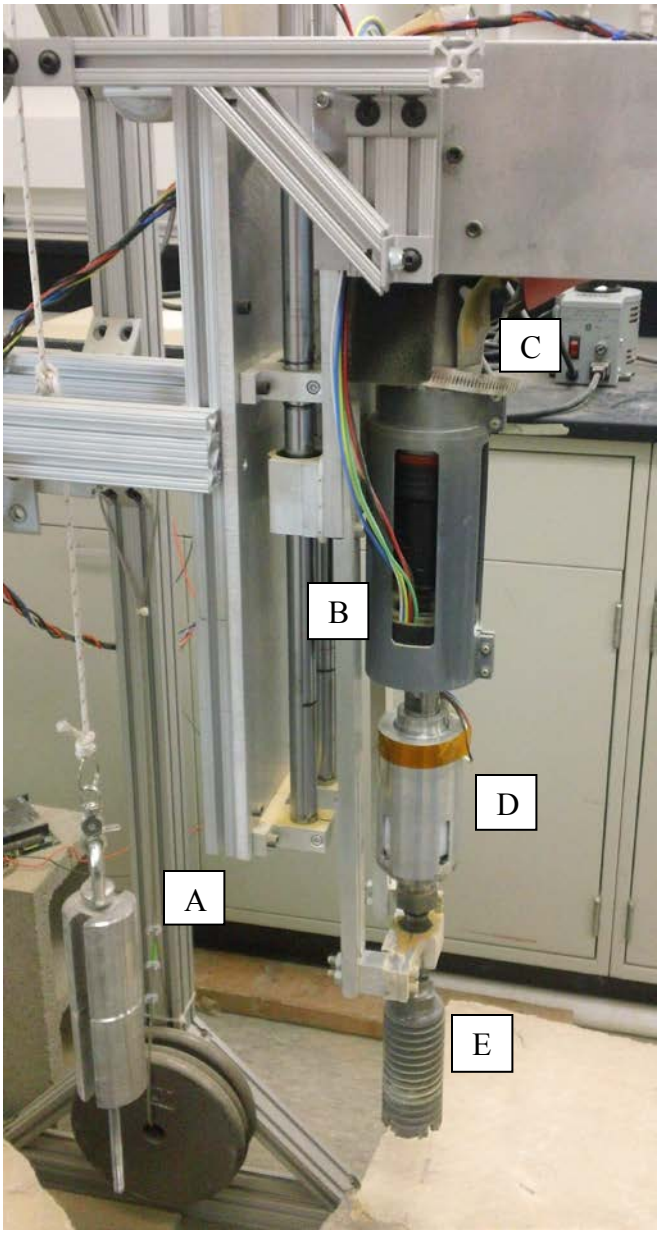
A. Experimental Setup



The top box is a function generator (model Tektronix AFG320). The LabVIEW program sends a user-defined frequency to it, where the signal will then be sent to the power amplifier (bottom box, model EIN 1140LA). As the signal is sent to the drill, it is also being read by the oscilloscope (middle box, Sony Tektronix TDS 7142) and sent back to the computer. The LabVIEW program then analyzes the signal and the feedback loop can send an updated frequency signal to the function generator again.



This is a screen capture of the LabVIEW program, "HillClimb". User inputs include input voltage, starting frequency, and duty cycle with a choice for length of time. The power in watts and the admittance are graphically displayed for the user.



This is the Hilti drill on the test stand. A pulley system (A) changes the preload on the bit by increasing or decreasing the weight. The drill (B) is controlled by a variable voltage provider (C) that causes rotation between 32% and 50% input. Any lower and rotation ceases; any higher and the test stand becomes less stable. The piezoelectric transducer is located at the end of the drill (D), and the drill bit attaches at the end of the transducer (E).