Ultrasonic Penetration of Granular Materials in Varying Gravity

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ABSTRACT

This paper describes the effects of ultrasonically-assisted penetration of granular materials, in high gravity situations. The experimental rig, instrumented to obtain penetration force, rate and power both with and without ultrasonic assistance, was used to drive a penetrator into a granular material inside the ESA Large Diameter Centrifuge at accelerations of up to 10 g during early September 2015. Ultrasonic penetration proved to be most beneficial at lower levels of accelerations, reducing the required overhead weight by 80%, and the total power consumption by 27%.

INTRODUCTION

The surface of other planets is often inhospitable. Even some of the most Earth-like locations, such as Mars, have radiation levels so high that radio resistant bacteria such as *D. Radiodurans* would struggle to survive over evolutionary timescales (Hassler 2014). However, some meters below the surface, the radiation drops to near terrestrial levels in an environment that appears to host volatiles and even brine. Accessing this environment is essential if we are to understand the history of other Earth-like environments, and some form of penetrator will therefore be required.

Drilling or penetration on solar bodies also poses another issue; the lower gravity results in a lower overhead weight that can be supplied to the drill. This weight-on-bit (WOB) is a vital aspect in drilling mechanics, with a lower WOB often resulting in less efficient drilling. Missions to other solar bodies also often rely on saving as much weight as possible, further limiting the maximum WOB that can used for drilling applications.

Previous work has shown that ultrasonically-assisted vibration of a penetrator can reduce force requirements by over an order of magnitude in granular materials (Firstbrook 2014), facilitating access in a low weight-on-bit scenario. Indeed the force may be lessened to such an extent that, under certain conditions, the reduction in actuation power required is more than the additional power consumed by the ultrasonics, reducing overall power consumption by almost a third (Firstbrook 2015b).

Spin Your Thesis campaign. The experiments described in this paper were conducted as part of ESA's 6th 'Spin Your Thesis!' campaign. This campaign allows a group of students access to the Large Diameter Centrifuge (LDC) at the European Space Research and Technology Centre (ESTEC) in the Netherlands. The diameter of the LDC, shown in Figure 1, is 8 meters, and allows testing in hypergravity conditions from 1 g up to a maximum of 20 g. This campaign occurs annually, and is open to any student from the ESA Member States.

Six testing gondolas are available to run simultaneous experiments, with an additional gondola located on the axis of the centrifuge to store equipment that could not handle the higher accelerations. Electrical connections can also be made between the gondolas. The maximum size of the experiment is limited by the size of the door to the gondolas, with a maximum clearance of 45 x 70 cm.

The aim of the experiments at the LDC was to investigate the force reductions and power saving capabilities of ultrasonic penetration at higher levels of gravity. By establishing trends with respect to gravity, it is possible that predictions can be inferred for low gravity applications, such as small landers on comets or other planetary bodies.

Figure 1. The Large Diameter Centrifuge. Experiments can be placed within the red gondolas, with the central gondola reserved for equipment that does not need to be subjected to high gravity.

MARTIAN REGOLITH

Martian regolith simulants. The term 'regolith' is often used to describe the granular material present on the surface of solar bodies. This paper will use the term 'sand' to describe a regolith simulant, with this experiment using a medium-fine, sub-rounded quartz based sand from the University of Glasgow. This sand, referred to as 'BP', has been used in previous tests (Firstbrook 2014, Firstbrook 2015b), and is similar to previously published regolith simulants (Scott 2012, Brunskill 2011). Two common methods of displaying particle distributions of sand are the percentage weight passing, shown in Figure 2 (a), and the percentage of total mass, shown in Figure 2(b).

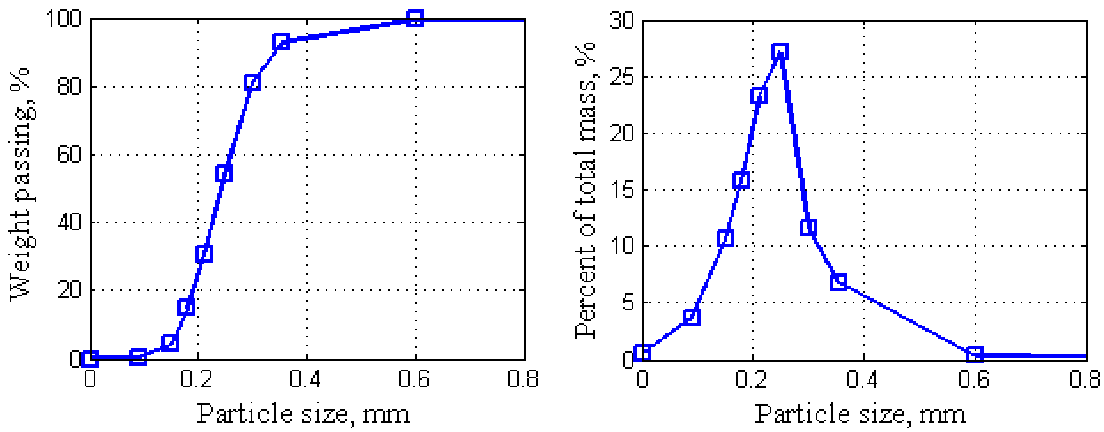

Figure 2. Particle size distribution of BP sand.

Sand preparation. The method in which a sample of sand is prepared can have a dramatic influence on the final bulk density and distribution. Small variations in the density of the regolith can have dramatic effects on the force needed for penetration (Seiferlin 2008, Firstbrook 2014), and thus is it imperative that proper care is taken in the preparation of sample of sands used for testing.

Low density samples of sand are prepared by allowing sand to fall at least 40 cm into the final sample container (Kolbuszewski 1961). This height ensures that the sand has sufficient time to reach terminal velocity and mix turbulently before settling in the final testing container. High density samples of sand are prepared by vibrating or shaking the container, thus settling the particles into a more compacted state.

Previous work involving ultrasonic penetration through granular material (Firstbrook 2014, Firstbrook 2015b) produced low density samples by allowing the sand to fall 1 m at a constant rate. This ensured that the height would always be greater than 40 cm, even as the container filled. To produce high density samples of sand this process was repeated, the container was vibrated until it had filled, and the total weight measured to calculate the density. In both cases, this method resulted in very small variations in density on the order of 0.5% over the whole experiment (Firstbrook 2014).

This method however is difficult to transfer over to the LDC experiment, due to the limited size of the centrifuge gondola, and as the total allotted experimental time at the LDC is limited to two and a half days it would not be feasible to open the gondola to replace the sand after each run. Therefore an automatic in-situ method by which the sample could be vibrated remotely was designed, thereby eliminating the need to spin down and safely access the centrifuge.

For this method, the container was filled with 7 kg of BP sand, and vibrated for a specific amount of time in order to fully reset the sand. To establish what duration of vibration was needed, and to verify whether this method could routinely produce consistent samples, a set of investigatory tests were taken. The container was vibrated at either 0.5, 1, or 2 minutes, and then used for a non-ultrasonic penetration test. This was then repeated 5 times for each vibration duration, with the force and depth recorded in each case. If the sand had not fully reset during the vibration, then consecutive penetration would display higher maximum penetration forces; a phenomenon observed in previous experiments in granular penetration (Seiferlin 2008, Firstbrook 2014). All durations of vibration showed deviations of only a few Newtons, suggesting that the sample of sand has been fully reset. To allow for the unknown behavior of sand at higher g levels, a vibration duration of 1 minute was chosen for the LDC experiments.

EXPERIMENTAL EQUIPMENT

Ultrasonic penetrator. The penetrator was a titanium horn designed and manufactured to resonate at 20 kHz at the L2 vibrational mode (second longitudinal mode). This resulted in a total length of 261 mm, with a maximum allowable penetration depth of 201 mm. This maximum depth is determined by the location of the ‘step’ in the shape profile, as shown in Figure 3. This step is a vital part of designing an ultrasonic horn, as a decrease in cross-sectional area amplifies the level of ultrasonic vibration. The specific shape of the horn results in different levels of amplification, or gain, of the horn (Amin 1995). The step-function provides the greatest amplification, and the ultrasonic horn used for these tests was experimentally measured to have a gain of 3.5. An ultrasonic transducer is connected to the horn via an internal axial grub screw to provide the ultrasonic vibration required.

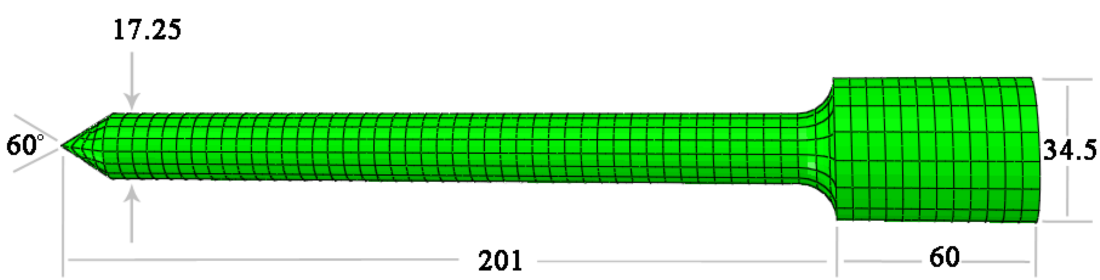

Figure 3. Size and shape of the ultrasonic penetrator used. Dimensions are given in mm.

Testing parameters. Previous tests into ultrasonic penetration (Firstbrook 2014, Firstbrook 2015b) have shown that ultrasonic vibration can reduce required force by a factor of 10, and reduce the power consumption by 30%. The aim of this experiment is to continue this work and investigate these effects at different levels of gravity, potentially aiding future missions on extraterrestrial bodies.

The two variables tested in this experiment are gravity and ultrasonic amplitude. Allowing for seven values from each, as well as repeating each test 3 times gives a total of 147 experimental runs, fitting within the allotted 2.5 days use of the LDC. The density of the sand is kept constant at 1.79 g/cc, as well as the penetration rate of 9 mm/s. One of the aims of this work is to extrapolate results to gravities lower than Earth's to predict performance if ultrasonically-assisted penetration were to be used on extra-terrestrial bodies. Therefore it is important to concentrate gravitational levels on the lower end of the scale, resulting in g levels of 1, 1.5, 2, 3, 5, 7, and 10 g chosen for these experiments.

Previous tests (Firstbrook 2015b) showed the optimum level of ultrasonic vibration in terms of total power consumption is around 0.5 µm. The seven ultrasonic amplitudes used for these experiments were chosen to concentrate around this region, resulting in ultrasonic excitation amplitudes of 0, 0.4, 0.5, 0.6, 0.8, 1.2, 1.6 µm, with 0 µm representing the non-ultrasonic case, and 0.4 µm being the lowest vibration level that can be achieved by the ultrasonic transducer.

Control mechanisms. The penetration rate was determined by the input voltage of the linear actuator, with 12 V corresponding to the maximum rate of 9 mm/s. The actuator contains an internal potentiometer, allowing accurate measurements of the extension of the actuator arm and therefore of the penetration depth.

An Ardunio circuit was used to remotely control the linear actuator (used to raise and lower the penetrator), as well as for controlling the vibrating motor (electric sander attached to the sand container) used for resetting the sand. The Ardunio was connected to the potentiometer in the linear actuator, and calibrated so that it would raise the penetrator to the same height, without over-extending and damaging the test chamber. The ultrasonic excitation amplitude and sander used to reset the sand could also be controlled by remote user input.

Experimental rig. The experimental rig, shown in Figure 4, uses a linear actuator to raise and lower a supporting crossbar on rails, upon which the ultrasonic penetrator is attached. This enables the actuator to provide the required penetration force, yet save a large amount of head space due to off-axis placement of the actuator. Each load-bearing component of the rig was modeled in finite-element analysis (FEA), to verify the structure would withstand the increased loading caused by hyper gravity (Firstbrook 2015a)

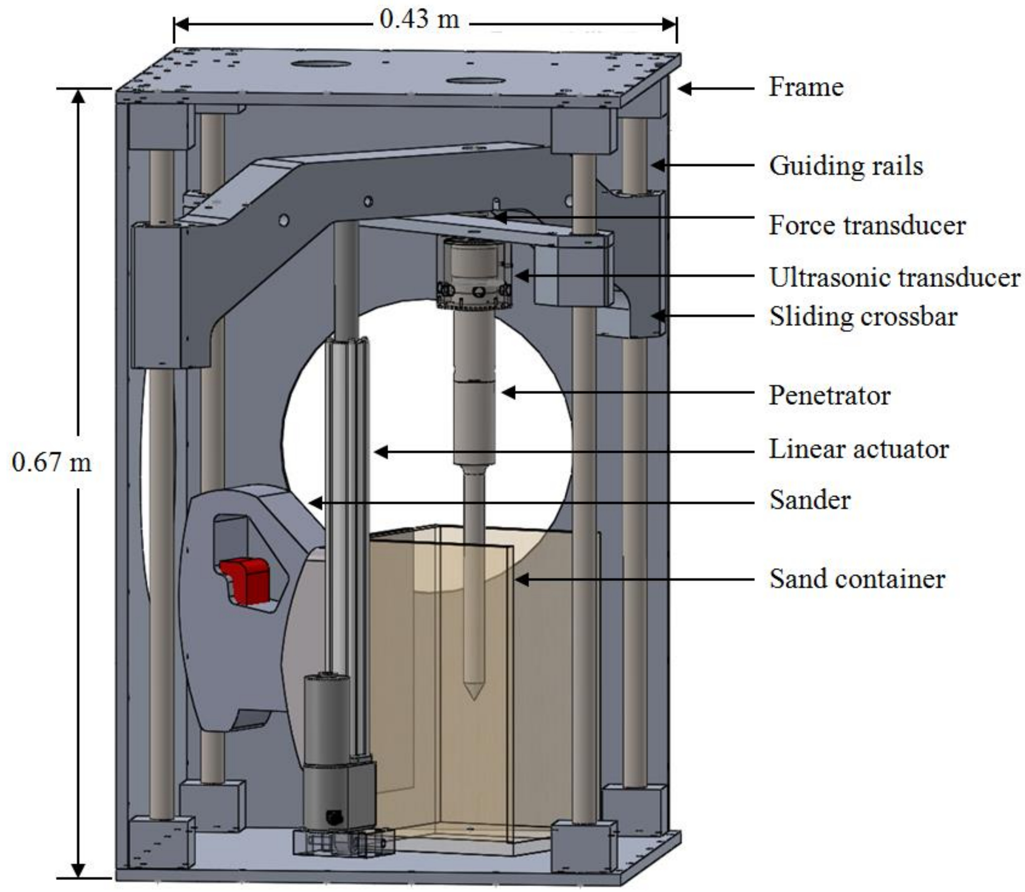

Figure 4. The experimental rig. The aluminum frame was designed to fit within the measurements of the centrifuge gondola doors.

Experimental procedure. MATLAB scripts were written to command the following steps:

1. Raise the penetrator up to the resting position.
2. Vibrate the sand container for 1 minute.
3. Spin the centrifuge to the chosen g level
4. Turn on the ultrasonic transducer to the chosen excitation amplitude.
5. Start measuring force, penetration depth, linear actuator power consumption, and ultrasonic transducer power consumption.
6. Lower the penetrator until the maximum depth has been reached.
7. Turn off measurement and ultrasonic power.
8. Spin down the centrifuge to 1 g (stationary).
9. Repeat from step 1.

Before placing the rig into the centrifuge gondola, the sand container was filled with 4.57 kg of BP regolith. With a minute of vibration, this created a consistent density of 1790 kg/m^3. Note that this is dependent on the mass of the sand, not the weight, and therefore remains independent of the g level.

RESULTS AND DISCUSSION

One of the aims of this test was to investigate how the ultrasonic capabilities varied with gravity. Figure 5(a) confirms that the force reducing properties of ultrasonic vibration (Firstbrook 2014) remain at higher levels of gravity. Figure 5(b) shows that higher gravity levels lead to high maximum penetration forces. In order to see a true representation of the improvements of using ultrasonic penetration, one must normalize all penetration forces to the non-ultrasonic case (i.e., the 0 µm excitation amplitude tests), for each level of gravity.

Unfortunately, the non-ultrasonic penetration tests were not able to be completed at 7 g and 10 g, due to the excessive forces anticipated. This means that we cannot normalize the results at 7 g and 10 g, thereby reducing our data set. Five gravity levels are still available however, and the results are shown in Figure 6. Here, it is possible to directly compare how ultrasonic vibration affects penetration in higher gravity, with a steeper gradient of curve suggesting a higher response to ultrasonics. The lower gravity results show more of an improvement than higher gravity, suggesting that penetration in high gravity is less sensitive to ultrasonic penetration. For example, using an excitation amplitude of 1.6 µm, the penetration force at 1 g is reduced by 80%, compared to just 70% at 5 g.

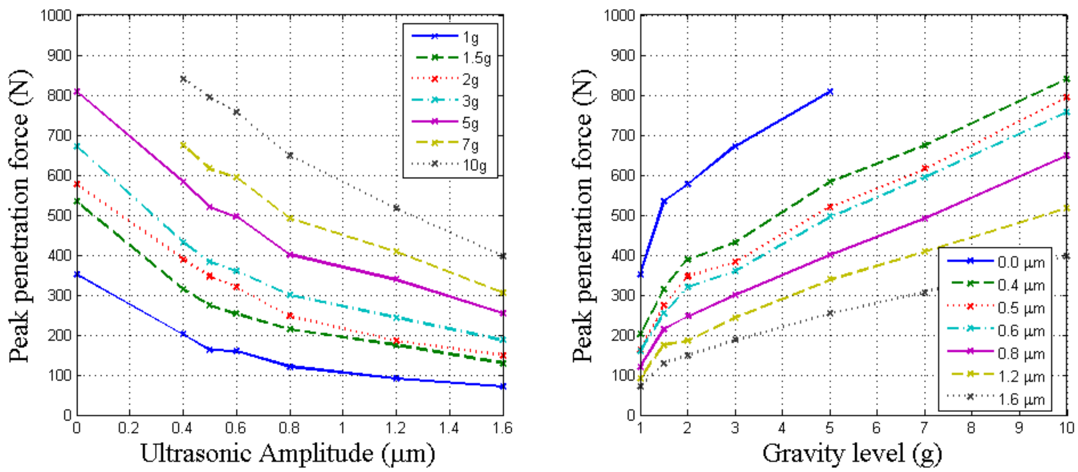

Figure 5. Maximum penetration forces as a function of (a) Ultrasonic excitation amplitude, and (b) 'g' level.

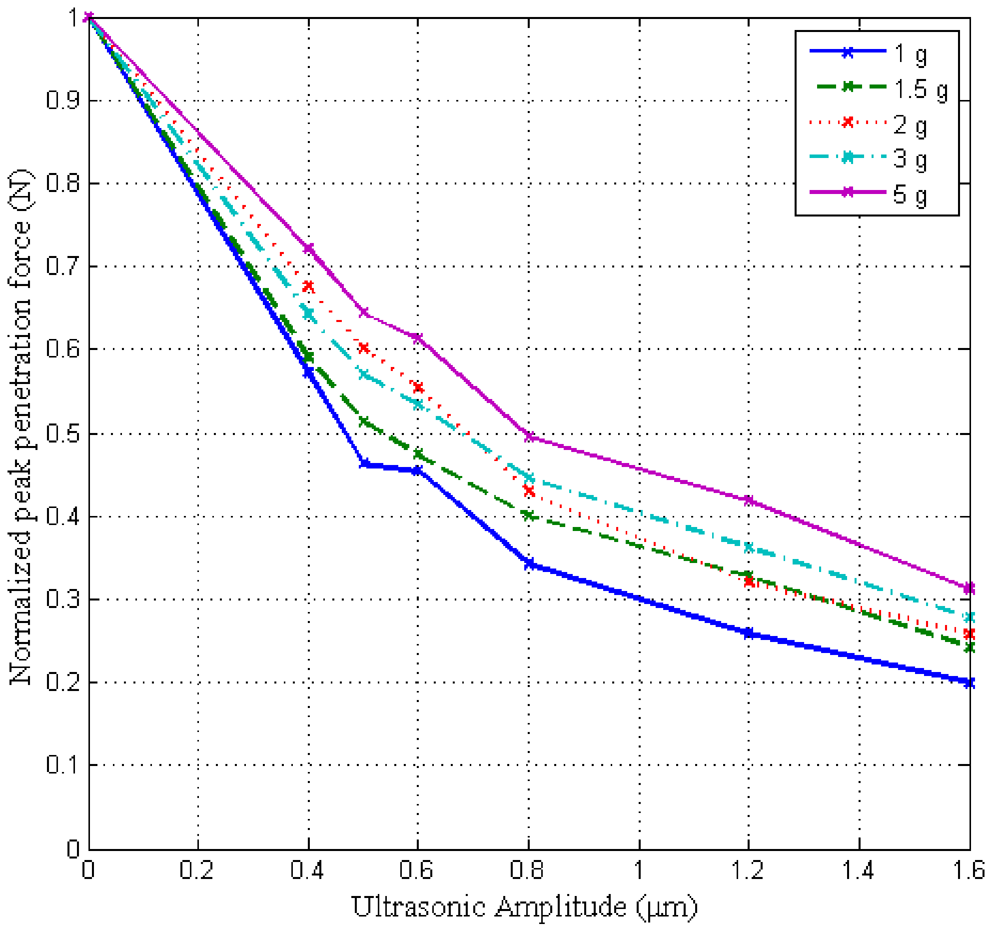

Figure 6. Maximum penetration force normalized to peak force encountered with ultrasonics off at that particular g level.

Ultrasonic vibration has also been shown to reduce the total electrical power consumed during penetration through granular material, by using an optimum level of ultrasonic excitation amplitude (Firstbrook 2015b). Figures 7(a) and (b) shows an example of the relationship between ultrasonic and actuator power consumed. Only the graphs taken at 1 g are shown for this instance, however similar plots exist at each level of gravity tested. The power consumed by the linear actuator was both directly measured, Figure 7(a), as well as calculated by multiplying the peak penetration force by the penetration rate of 9 mm/s, Figure 7(b). Figure 7(b) clearly shows a decrease in the total power consumption, corresponding to an ultrasonic excitation amplitude of 0.5 µm.

Again, it is possibly more beneficial to compare the normalized power-consumption results, shown in Figure 8. Here, the total power consumption for each value of ultrasonic amplitude was divided by the total power consumption at 0 µm. The greatest reductions in total power consumption occurred at 1 g and 1.5 g, with a saving of 26% and 27% respectively. The lowest reduction occurred at 2 g and 5 g, with a saving of 17% and 16% respectively. The power saving at 3 g lies between these values at 22%.

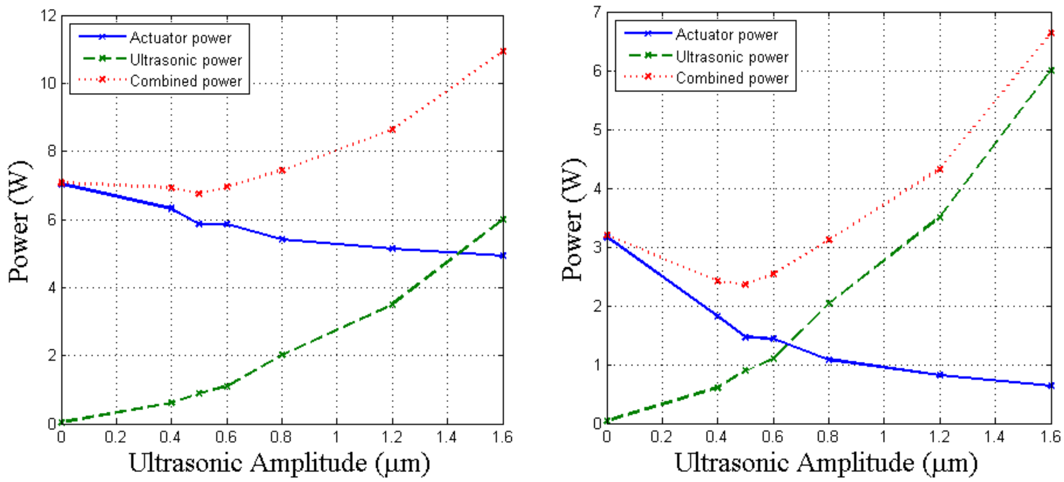

Figure 7. Example of the total power consumption of actuator and ultrasonic power, taken at 1 g for this example. The measured actuator power is shown in (a), whereas the calculated 'perfect motor' (force times penetration rate) power is shown in (b).

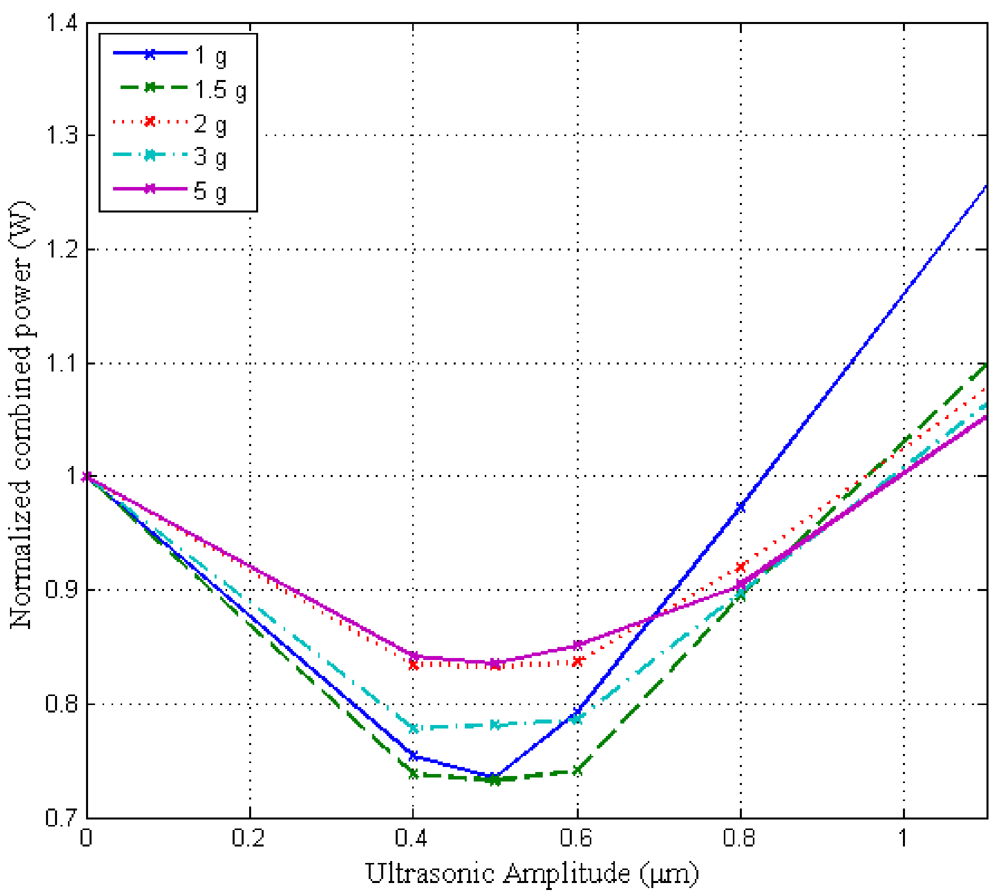

Figure 8. Total power consumption as a function of excitation amplitude, normalized to the non-ultrasonic power.

CONCLUSION

As is seen in Figure 6, lower levels of acceleration show a greater sensitivity to the force-reduction capabilities of ultrasonically assisted penetration. This result is particularly beneficial to space applications, as Earth has the highest gravity of any rocky body in our solar system. If we extrapolate this trend to gravities lower than Earth, then we can infer that ultrasonically assisted penetration would have a *greater* effect, requiring much less overhead force than with non-ultrasonic penetration.

The perfect-motor power is used instead of the measured power of the actuator. This is due to the fact that the motor used in the actuator is quite inefficient, resulting in power consumptions of above 5 W even without any loading, which are too high to accurately discern any decreases in total power. It is encouraging to see that the largest saving in power consumption occurs at the two lower levels of acceleration and the lowest reduction at the highest level of acceleration, but the results at 2 g and 3 g seem to not fit within this general trend. A non-ultrasonic penetration at 7 g and 10 g would have helped establish a trend in this regard, as well as conducting experiments in gravities less than 1.

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