PREPARATIONS FOR VARIABLE-GRAVITY REGOLITH PENETRATION WITH AN ULTRASONICALLY-ACTIVE PROBE

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ABSTRACT

The set of experiments proposed in this paper intend to investigate the properties of ultrasonic penetration through granular materials in hypergravity. As part of ESA's 6th 'Spin Your Thesis' campaign, the University of Glasgow will be allowed to use the Large Diameter Centrifuge at the ESTEC facilities in Noordwijk, Netherlands, to achieve these hypergravity conditions. This paper describes the progress of the design and manufacture of the experimental apparatus, analysis of structural integrity to insure the rig can be subjected to the rigors of hypergravity, and discussion of the anticipated results and implications.

1. INTRODUCTION

The search for life in the solar system is not only a concept of science fiction, but an exciting and active field of research. Most of our efforts, such as the current Mars Science Laboratory aboard Curiosity, have concentrated on Mars, but many other bodies in the solar system like the moons of Jupiter and Saturn also show promise. Mars in particular suffers from two main complications: the lack of appreciable atmosphere, and the lack of a significant magnetic field. On Earth, both of these act to shield us from harmful solar radiation. On Mars however the surface is much more vulnerable to this radiation, with the MSL recording a background surface radiation of 100 times than that on Earth [1]. This chronic level, equivalent to a mammogram a day, is too high for even the highly radio-resistant bacteria *D. Radiodurans* to survive on evolutionary time scales.

Radiation levels decrease beneath the surface of Mars due to more shielding mass, reaching adequate shielding for *D. Radiodurans* long-term survivability at 1 m, and Earth surface equivalent levels at 3 m depth, potentially allowing many more organisms to survive. This illustrates the importance of the ability to efficiently burrow several meters beneath the surface of Mars. To date, we have not gained access to depths past a few centimetres. A major aspect of this is fact that drilling in low-gravity environments poses a problem of supplying adequate weight-on-bit (WOB) due to reduced lander or rover weight. Power availability is also an issue with smaller craft, with every watt contested over by increasing numbers of scientific instruments on missions.

The Philae lander, currently on comet 67P, is a fitting example that both of these issues are still plaguing missions today. The harpoon, used to anchor the craft to supply greater WOB, did not deploy, and the craft bounced several times before eventually settling in a recess on the surface. Without the anchor, Philae only reacts a near negligible force on the surface, and was unable to hammer more than a few millimetres through the surface [2]. The recess in which Philae landed is blocking most of the light reaching Philae, resulting in reduced illumination on the solar panels and insufficient power for any communications. A drill system that will be able reach the desired depth with a lower WOB and lower power consumption would be ideal for this sort of situation. Previous experiments involving ultrasonically assisted penetration has shown reduction of WOB requirements by over an order of magnitude [3].

2. ULTRASONIC PENETRATION OVERVIEW

A custom rig was manufactured to measure forces utilising ultrasonic penetration [3]. The penetrator was a titanium spike, designed to resonate at 20 kHz. An ultrasonic transducer provides the vibration, with excitation vibration amplitudes up to 10 µm. A general illustration of the apparatus is shown in Fig. 1. The force transducer, connected to the top plate, serves as the sole point of contact for the actuator, cage, transducer, and penetrator. This ensures that any force reacted from penetration is directed entirely through the force transducer and can be measured accurately. This method also resulted in a very tall, narrow rig, standing at 1.6 m.

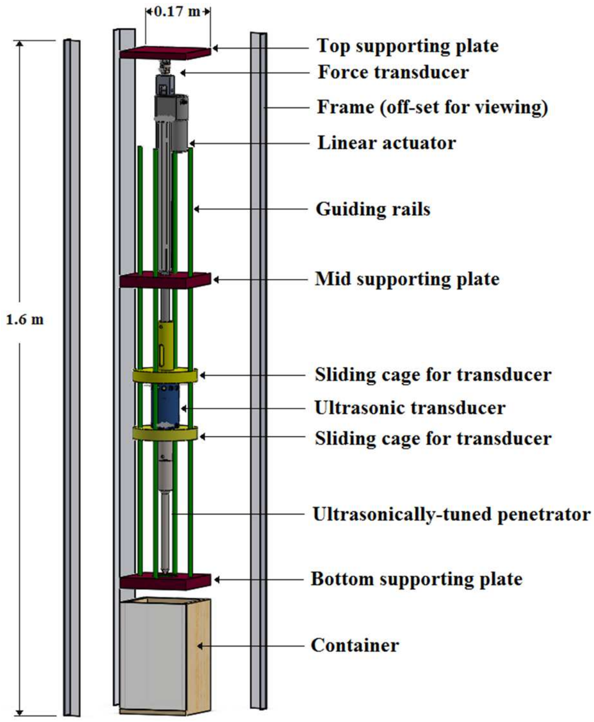

Fig. 1. Penetration rig apparatus. The frame is bolted to the three supporting plates, and the transducer cage is free to slide up and down along the rails between the mid and bottom plates.

The entire experiment consisted of using two different penetration rates, five different regolith simulants, two different relative densities, and four values of excitation amplitude (which included 0 μm to signify a standard static penetration). Reference [3] presents the full results from these experiments, with a sample result shown in Fig. 2. As can be seen, the force drops sharply for ultrasonic penetration, however diminishing returns are present for higher amplitudes.

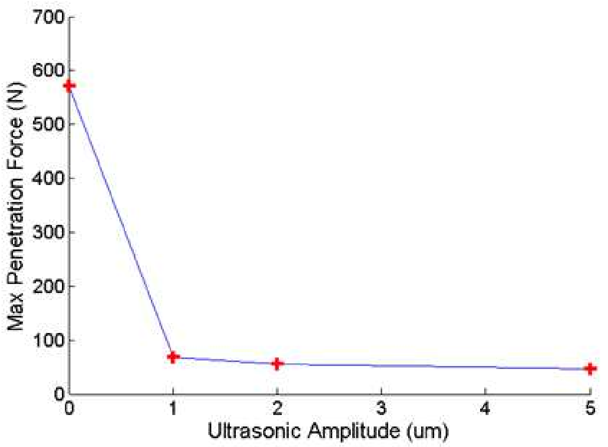

Fig. 2. Example of the maximum penetration force encountered for four penetrations using four different values of ultrasonic excitation amplitude. This specific test was conducted in high-relative density sand, at a low penetration rate.

Every test was also followed by 5 consecutive penetrations into the same sample, resulting in increased penetration forces across the board. This behaviour displays settling effects in the sand, as each penetration compacts the material further, causing higher penetration forces for subsequent runs [4]. To test the extent of this compaction and the effects of ultrasonic penetration, two additional tests were run. For one test, the first (primary) penetration used a 5 μm ultrasonic vibration, followed by a static (non-ultrasonic) secondary penetration. The other test was a static penetration for both primary and secondary, with the results shown in Fig. 3.
Both secondary penetrations result in the same final penetration force, but the force profile along the penetration depth is quite different. The run with an ultrasonic primary had a steadier and predicable increase in force, whereas the run with a static primary starts with a lower penetration force, which quickly ramps up towards the end. A penetrator must displace sand as it is pushed through regolith, usually by compressing the sand immediately surrounding it. The steadier profile of the secondary penetration with an ultrasonic primary, suggest that the resulting fabric of sand is much more homogeneous, resulting in a smoother secondary penetration.

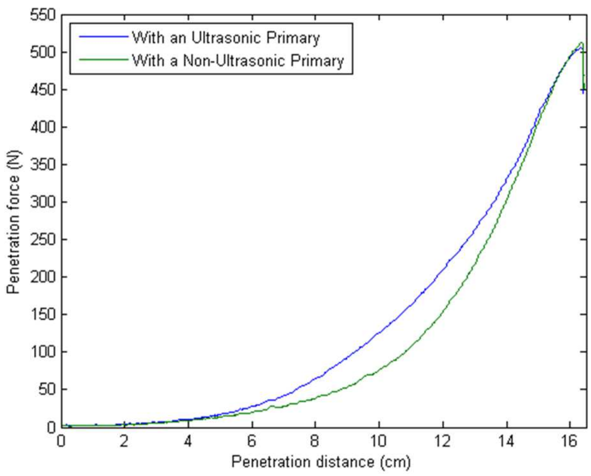

Fig. 3. Static secondary penetrations with either an ultrasonic or static primary. This test was conducted in high relative density sand at a fast penetration rate, using 5 μm vibration amplitude for the ultrasonic primary.

It is clear that ultrasonics has an effect on the fabric of the sand, and to fully understand the processes involved further tests in various levels of gravity are warranted. This could potentially be used to formulate an empirical model that would be able to predict required penetration forces or power consumption.

3. THE 'SPIN YOUR THESIS' CAMPAIGN

The 'Spin Your Thesis' campaign is run every year by ESA, allowing 4 teams of students the unique opportunity to perform experiments in hypergravity conditions. The selected teams are allowed experimental time on the Large Diameter Centrifuge (LDC, Fig. 4) at the European Space Research and Technology Centre (ESTEC) in the Netherlands. With a diameter of 8 meters, the LDC can provide gravitational accelerations from 2 to 20 g_0 (where $g_0 = 9.81$ m/s^2), with experiments in one of the six gondolas that can be attached to the arms.

Fig. 4. The Large Diameter Centrifuge (LDC). (courtesy ESA)

Our experiment will be using the LDC to test the effectiveness of ultrasonic penetration through granular material in gravitational environments up to a maximum of 10 g_0. Whilst all other terrestrial bodies in our solar system have a lower gravitational field than on Earth (i.e. $g < g_0$), it is still valuable to conduct experiments in hypergravity. Currently, microgravity experiments are limited to either free-fall tests (such as parabolic flights and drop towers) or in-orbit tests (such as experiments on the ISS). Free-fall tests can only be sustained for around 20 seconds, and in-orbit tests are only permitted after extensive consideration.

High gravity tests in the LDC allow us to conduct experiments in a varying gravitational environment, providing the opportunity to create empirical models for penetration and drilling. It offers significantly longer experimental time compared to microgravity methods, and by extrapolation the results could possibly be used to predict regolith penetration in lower gravity. We intend to use the LDC for three main aims:

1. Measure the penetration force required in various levels of gravity, and compare it against predictive models from the literature.
2. Investigate the WOB reduction benefits of ultrasonically assisted penetration, and examine how this varies with gravity.
3. Measure the power consumption of ultrasonic penetration, and attempt to establish the minimum power required for maximum force reduction benefit.

To achieve these aims, we first need to design a rig that can fit within the dimensions of the LDC gondolas (shown as the red containers in Fig. 4).

3.1 Design considerations

Re-designing the rig to fit within the gondola was a large issue to overcome, as the rig used in previous ultrasonic experiments (Fig. 5) stands at over 1.5 m tall, whereas the door clearance to the LDC gondolas is 45 x 75 cm, with a recommended 43 x 67 cm size limit to allow for ease of manoeuvrability. Significant alterations to the penetration rig design were needed in order to fit within the given dimensions, saving height at any point possible.

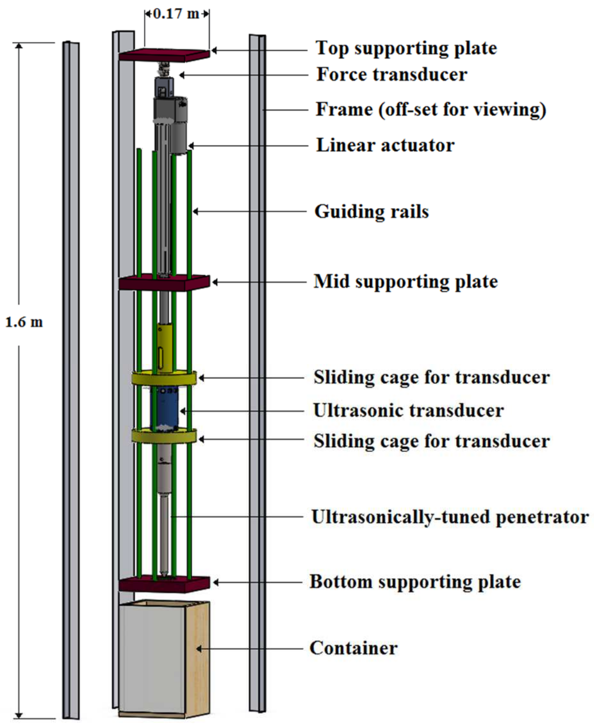

Fig. 5. The ultrasonic penetration apparatus used in previous tests [3].

The ultrasonic transducer for this rig requires a cage to contain it, shown in Fig. 5, as the actuator cannot connect directly onto the case due to the placement of the power plug at the top of the case, shown in Fig. 6a. The transducer also contains a fan to help cool the piezo-ceramics whilst in operation. The fan is normally only required at very high powered situations, and would not be needed for the relatively low power of our proposed experiments (roughly 10 W at maximum consumption). A new transducer case was designed, removing the fan and positioning the power plug to the side, allowing a direct connection to the top of the case, shown in Fig. 6b. Holes in the side of the case will allow air to flow and provide a passive cooling system. This design saves 6 cm by removing the fan and a further 14 cm by positioning the power plug to the side, thus removing the need for a transducer cage.

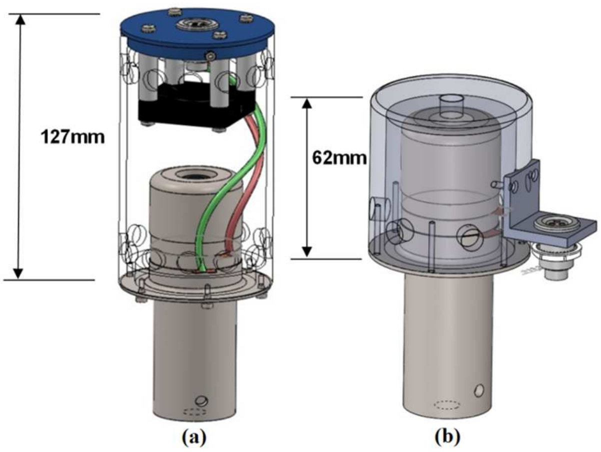

Fig. 6. Comparison of lengths of transducers. The new design removes the fan and re-positions the power input to the side.

Whilst altering the transducer case provides us with a much need reduction in height, more drastic measures are required in order for the rig to fit within the recommended 67 cm height limit. The sand container, ultrasonic horn, transducer, and actuator, are all required to be placed on of top of one another so that all reacted force can travel directly through the force transducer located at the top of the rig. All of these components are supported solely by the force transducer, ensuring all recorded measurements are accurate representations of the penetration force. However, the physical sizes of these components, when placed in this linear fashion, combine to be much more than the allowable size of the gondola.

To solve this issue, it was decided to move the linear actuator to be parallel with the sand container and penetrator, rather than axially above them. In this set-up, instead of pushing the penetrator down, the actuator pulls a connecting crossbar, which links the penetrator and actuator together and thus allows the penetrator to push through the sand. This 'folded' design saves a significant amount of height at the expense of additional width, of which we are not so tightly constrained. Four sets of rails provide stability, with the crossbar free to slide vertically along it on linear bearings set within the material, as shown in Fig. 7. An off-set motor attached to the side of the sand container will provide the ability to vibrate and reset the sand remotely between tests, in order to avoid the settling effects seen in consecutive penetrations [4].

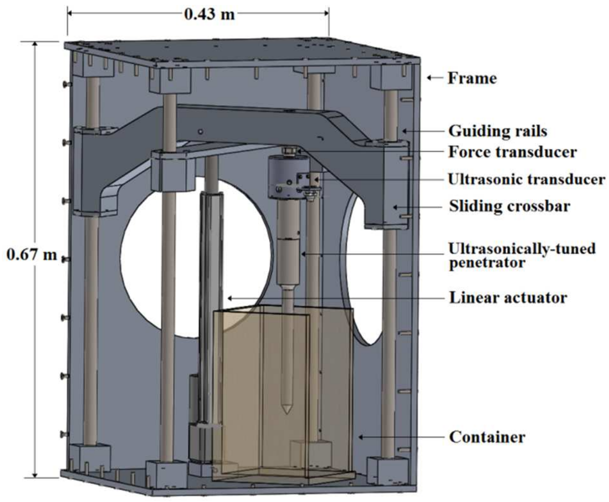

Fig. 7. The newly designed ultrasonic apparatus for use in the Large Diameter Centrifuge.

3.2 Stress analysis

Using this 'folding' technique discussed above, we reduce the height by a large amount. However, doing so requires that the applied force is off-axis with respect to the penetrator. This will create a high torque within the sliding cross bar, as the applied force will act to cause it to bend and twist. Careful consideration of the stresses within the material is needed, especially as the rig will also be subjected to high levels of gravity. The Finite Element Analysis (FEA) software used to analyse the displacements and stresses of the apparatus components was Abaqus 6.14 by *Dassault Systèmes*. All structural components apart from the rails and transducer case are designed to be manufactured from aluminium alloy 6082 T6 for a light weight, study structure. The newly designed transducer case is stainless steel alloy 1.4305 for its high strength properties, and the rails are tool steel for its superior hardness.

3.2.1 Sliding crossbar

The linear actuator is rated to a maximum of 1,000 N, however it was noted in previous tests that it could reach maximum forces nearer 1,300 N. It can damage the internal motor to sustain forces this high, so care will be taken to avoid this possibility. Note that this force is independent of gravity, as it is simply the amount of force it can provide. For simulation purposes, forces of 1,500 N were used to incorporate a margin of error.

The distance between the actuator and penetrator fixtures on the sliding crossbar were minimised in order to reduce the torque created within the material. As the actuator and penetrator fixing are off-set from each other, the sliding crossbar was analysed with a 1,500 N upwards loading at the penetrator fixture, and a 1,500 N downwards loading at the actuator fixing. The sliding crossbar is quite a complex design to model, as it is under two opposing loads, yet is free to slide vertically along the rails. A fixed, stationary point is normally required for stress analysis, so two simulations were run where either the actuator or the penetrator fixture were taken as the stationary surface, whilst the other fixture was subjected to its respective loading. This approximation will serve to give a good representation of the deflection and stresses expected in the cross bar, with the magnitude of deflection shown in Fig. 8

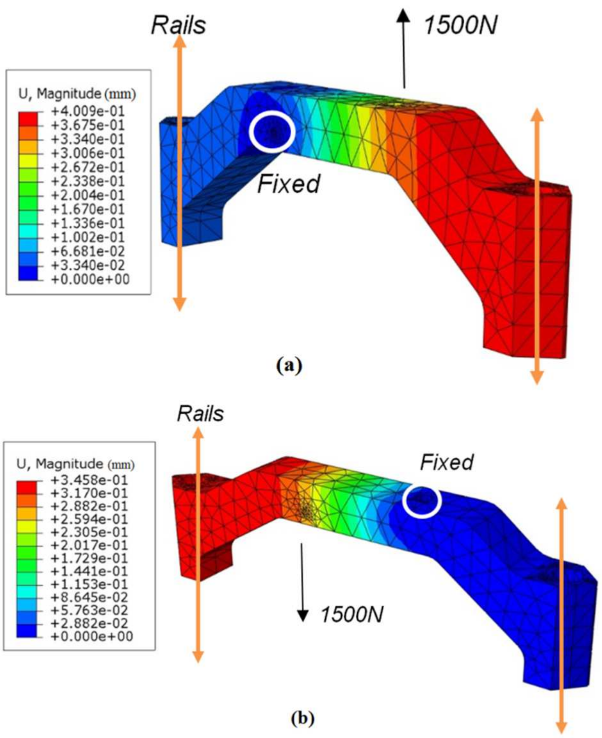

Fig. 8. Simulated deflection of the crossbar, with (a) taking the actuator fixture as the stationary point, and (b) taking the penetrator fixture as the stationary point.

From the analysis, it can be seen that the maximum deflection of the crossbar never exceeds 0.4 mm at maximum loading, a deflection that is manageable for the tool steel rails and bearings. The stresses, not shown, reach a maximum of 140 MPa, below the proof stress of aluminium of 290 MPa [5].

3.2.2 Rig frame

The first design of the frame to contain the LDC rig used thin cross-supports of aluminium to hold everything together. This ultimately proved to be too complex, as it relied on very precise measurements and angles to avoid clashing with other components of the frame. The decision was ultimately taken to take strength, simplicity, and manufacturability into account, whilst allowing accessibility throughout the rig for the experimental apparatus within the frame. The design is based on a plate of metal that will be bolted to the roof and base of the rig on each side. Each plate has a 250 mm access hole and each plate is also bolted to each other for extra support, as can be seen in Fig. 7 (note, two panels have been removed for ease of viewing the interior of the rig).

The frame itself will be under two main loads whilst in the centrifuge. The sustained 10 g_0 within the gondola will make the entire frame heavier, so it will need to be able to support itself in this higher gravity. The off-axis force created by the actuator and transducer will also act to push the frame diagonally to one side. Abaqus was able to model a 10 g_0 loading directly, shown in Fig. 9a, whilst a 500 N diagonal load to the top of the frame was used to simulate the force resulting from the torque in the crossbar, shown in Fig. 9b.

The deflection of the frame being subjected to hypergravity is 0.015 mm, whilst the deflection caused by the torsion in the crossbar is a maximum of 0.001 mm. These deflections are almost negligible when compared to the size of the frame, and will not impede the smooth running of the experiment. The stress on the frame from hypergravity reached 850 kPa, whilst the stress from diagonal loading reached 45 kPa. Again, both stresses fall far below the proof stress of 280 MPa for aluminium alloy 6082 T6.

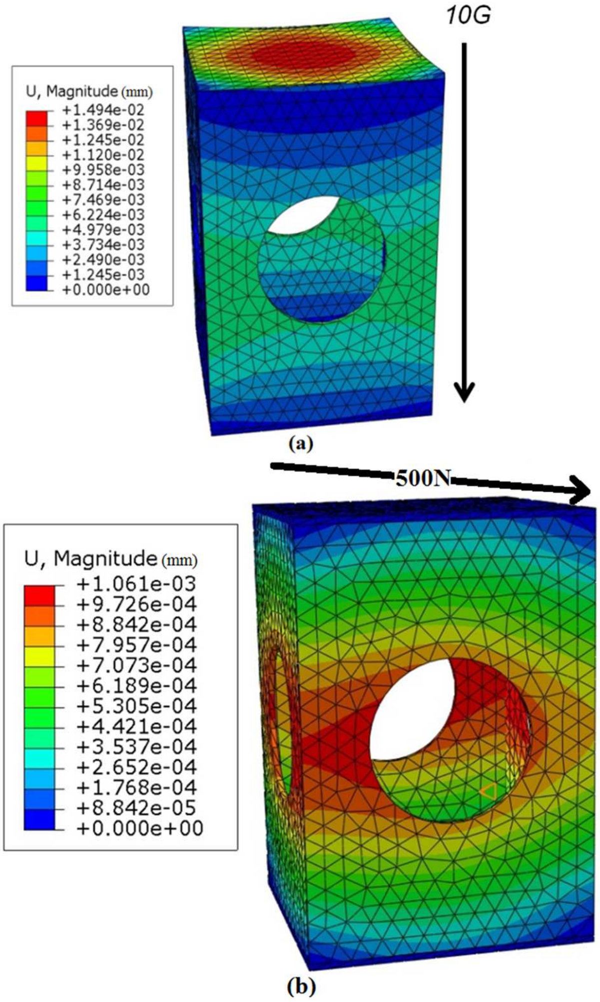

Fig. 9. Simulated deflection of the frame, with (a) simulating 10 times Earth's gravity, and (b) simulating the diagonal force caused by the crossbar.

3.2.3 Transducer case

The new design of transducer cap, shown in Fig. 6b, forgoes the fan and allows a direct fixture to the top of the case. The case will connect to the bottom of the force transducer via a grub screw, with the top of the force transducer connecting directly to the crossbar. A simulated 1,500 N force was applied to the fixture on the steel case, with the resultant deflection shown in Fig. 10.

A deflection of 0.003 mm is again negligible, and there is no danger of the top of the case bending so much that it could touch the piezo-ceramics inside. Stainless steel 1.4305 was chosen as the material, as it was discovered that the aluminium alloy used for the rest of the apparatus would fail for this particular application, due to the high force and low contact area involved. The stress on the top of the case reached 12 MPa in simulations, an order of magnitude below the proof stress of 190 MPa for this material [6].

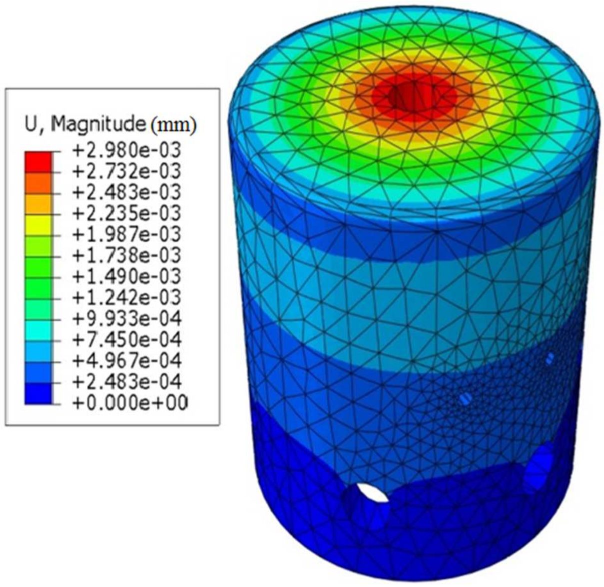

Fig. 10. Deflection of the new design for the stainless steel ultrasonic transducer case. A force of 1,500 N was applied to the fixture at the top of the case.

4. ANTICIPATED RESULTS

At the time of writing, manufacture of the apparatus has just begun, so no direct results are available. However, it can be extremely valuable to attempt to predict the results of the experiment with the information available to us. To this end, we will address the three main aims discussed earlier in the paper.

Perhaps the most topical result is discovering how the force-depth profiles change with gravity, as this has direct implications on interplanetary missions. There have been attempts at formulating equations to predict the force profiles of penetration through granular material, and these have shown promising results when compared to real data from previous missions such as Apollo 14-16 [7]. Sand is inherently a chaotic system though, and it is incredibly difficult to account for all variables.

It has been noted that one of the main contributing factors to penetration force through granular material is the relative bulk density of the regolith [4]. Higher density sand leads to higher penetration forces, and the models predict that sand can become more compacted at high gravity, and therefore a higher density [7]. However, the density of a given sand can only reach an absolute maximum value, with relative densities of 80+% achievable even in Earth's gravity [8]. Since density is capped at a maximum, it is expected that with increasing gravity, the penetration force will also reach a maximum value, as shown in Fig. 11. It is possible that as we approach this limit, other factors such as the unit weight of the regolith (which increases linearly with gravity) could take-over as the driving factor of penetration force. In this case, the maximum force would still gradually increase albeit at a much lesser extent than at lower levels of gravity.

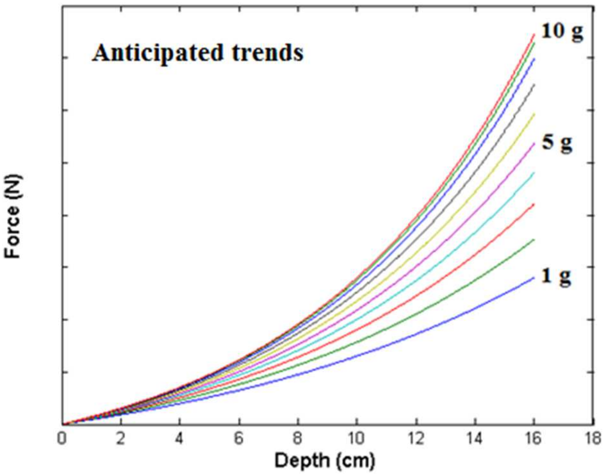

Fig. 11. Penetration force profiles under an increasing level of gravity.

Based upon experiments using high speed video to record the effect of ultrasonic vibration on sand, it is likely that the force reduction from using ultrasonic penetration does so by stimulating the particles of sand, causing them to move freely and avoid being locked. Whilst the specific method in which is does so is unclear without further testing, it is reasonable to assume that higher gravity would dampen this motion, thereby reducing the effectiveness of ultrasonic vibration. There have been very few investigations into the direct application of ultrasonic vibration on granular material in the literature, so this particular experimental aim is difficult to predict. However, based on the assumptions above, it is anticipated that the Max force vs. Ultrasonic amplitude curve will tend to flatten out with increasing levels of gravity, as shown in Fig. 12. These sets of measurements are based upon measured results that are shown in Fig. 2.

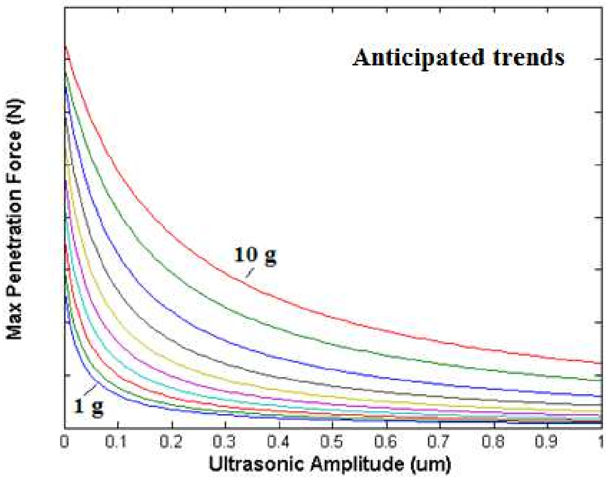

Fig. 12. Maximum penetration forces as a function of ultrasonic amplitude. The 1 g curve would be directly related to the results seen in Fig. 2.

The power consumption of the linear actuator is directly proportional to the force it is pushing with. Since ultrasonic vibration reduces the required penetration force, less power will be consumed by the actuator. Higher ultrasonic amplitudes lead to larger actuator power reductions, with an expected trend shown by the ‘Power of linear actuator’ curve in Fig. 13. However, higher ultrasonic amplitudes require more power to sustain, meaning the power consumed by the ultrasonic transducer itself increases with amplitude. Since one decreases and the other increases with amplitude, it is expected that there will be an amplitude where the sum of actuator and transducer powers is at a minimum, identified by the dashed line in Fig. 13. This amplitude will correspond to the optimum point in terms of power consumption, reducing the overall power requirements of a regolith penetrator.

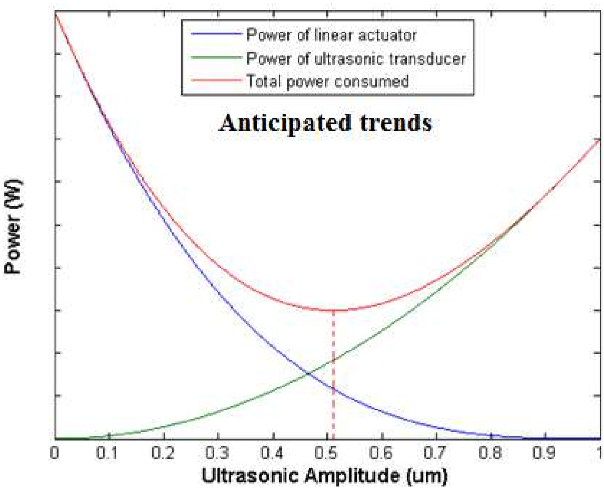

Fig. 13. Power consumption levels of the linear actuator and ultrasonic transducer.

5. CONCLUSIONS

Power availability and weight-on-bit requirements of landers or rovers for surface exploration missions are often limiting factors, especially for smaller craft. Ultrasonically-assisted penetration has shown promise at reducing WOB requirements, and the experiments presented in this paper aim to consider its power reduction qualities as well. These experiments will be conducted in hypergravity (up to 10 g_0), in an attempt to provide empirical data that could be used to predict the effectiveness of ultrasonic penetration at lower levels of gravity.

The high gravity environment of these experiments presents a unique challenge in designing an experimental apparatus. Stress and deflection simulations have been conducted to ensure the rig is able to perform the required experiments in high gravity. It is hoped that the discussion of anticipated results could open up a dialog with other researchers in the field of sub-surface planetary exploration.

6. ACKNOWLEDGMENTS

The authors would like to thank the ESA Education Office and the Spin Your Thesis! program for providing the financial support and opportunity to conduct experiments at the Large Diameter Centrifuge this September.

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