Experimental Investigation of Bucket Excavation Force Reduction with an Ultrasonic Leading Edge. E. T. Rezich[1], M. P. Proctor[2], K. A. Johnson[3], F. Thomas[4], A. Schepelmann[5], [1]NASA Glenn Research Center 21000 Brookpark Road, Cleveland, OH 44135 erin.t.rezich@nasa.gov, [2]NASA Glenn Research Center 21000 Brookpark Road, Cleveland, OH 44135 margaret.p.proctor@nasa.gov, [3]NASA Glenn Research Center 21000 Brookpark Road, Cleveland, OH 44135 kyle.a.johnson@nasa.gov, [4]NASA Glenn Research Center 21000 Brookpark Road, Cleveland, OH 44135 fransua.thomas-1@nasa.gov, [5]NASA Glenn Research Center 21000 Brookpark Road, Cleveland, OH 44135 alexander.schepelmann@nasa.gov.

Introduction: Excavation of lunar regolith is critical to the development of a sustainable human presence on the lunar surface by enabling large-scale production of life-sustaining commodities. While the near-term target resources for NASA are water and oxygen, useful for astronaut life-support and rocket fuel production, a host of other interesting possibilities for lunar regolith utilization exist, almost all of which require regolith excavation [1]. The Moon poses unique excavation challenges compared to Earth, including a gravity field that is about one sixth that of Earth's, jagged particle shapes including agglutinates and glasses, and small average particle sizes (~70μm). Together, these amount to complex excavation conditions [2].

Sampling lunar regolith has proven difficult at increasing depths; to reach desired coring depths, core samplers flown on Apollo missions required higher than expected work and force, as well as hammer blows [3]. Terrestrial excavation devices typically rely on the weight of the machine to provide resistance to the cutting forces of the tool. With lunar gravity being one-sixth that of Earth gravity, the vehicle mass needed to excavate lunar regolith could become prohibitively large or result in tipping the excavation equipment on the lunar surface.

Tools with ultrasonic leading edges may reduce required excavation forces and may reduce experienced reaction forces for lunar excavation, enhancing large-scale regolith extraction on the Moon . Sub-scale testing using ultrasonic probes in compacted GRC-3, a lunar regolith simulant, suggests meaningful force reductions of up to 70% in laboratory conditions [4]. This technology has recently been integrated into an excavation bucket where the tool's leading edge is an ultrasonically vibrating blade. We theorize that the vibration of the leading edge will fluidize the granular soil, thereby creating a less resistive soil state in the immediate vicinity of the leading edge. This study investigates the usefulness of this phenomenon on a full-scale prototype bucket design where trajectory speed and vibration condition (on or off) are varied. This paper presents measured forces and torques acting on a bucket with an integrated ultrasonic leading edge for excavation tasks in compacted GRC-3b lunar soil simulant.

Test article: The prototype ultrasonic bucket shown in Figure 1 is made of aluminum, has a 15.4 cm wide and 36.8 cm high opening that is 32.7 cm deep. The ultrasonic blade leading edge is made of Ti-6Al-4V and is 15.24 cm (6 in) wide with a 11.45 degree wedge. The blade is powered by Sonics and Materials VCX-500 ultrasonic converter that has a maximum power output of 500 W. This system is used to drive and control the vibration of the blade at 20 kHz with a 54 microns amplitude in the longitudinal mode. The ultrasonic blade is protected from excessive lateral loads by upper and lower plates that cover the blade so that just 5 cm of the blade is exposed. These plates are not in contact with the blade such that the bucket itself is isolated from the forced vibration and only the blade is dynamic. Slots in the blade exist for tuning purposes, and holes in the bottom plate allow soil pushed into the gaps between the blade and the cover plates during excavation to escape to prevent overheating and restriction of blade motion. A cylindrical-shaped cover protects the ultrasonic converter and stainless steel tube protects the converter power cable on the bottom and back of the bucket, respectively, from contamination and wear.

Figure 1. Ultrasonic Bucket prototype test article.

Test Apparatus: Tests are performed using the Advanced Planetary Excavator (APEX), shown in Figure 2, which is a four degree of freedom robotic manipulator located at NASA Glenn Research Center's Excavation Lab, one of the mTRAX Planetary Exploration Labs. The robot provides a modular platform to measure forces and power needed to excavate granular lunar regolith simulants at various compaction levels using tooling at various rake angles and tool trajectories. A 6-axis force and torque transducer located between the manipulator output and tool end effector measures excavation forces and torques, while a real-time data acquisition system simultaneously logs the full state of the robot including power to each of the joint actuators [5, 6, 7].

Figure 2. The Advanced Planetary Excavator (APEX) arm in the Excavation Lab at NASA Glenn Research Center. The Ultrasonic Bucket is attached as the end effector tool for the arm.

Test Procedures: The soil was loosened, leveled, and compacted prior to each test. The bucket tip test trajectory consisted of three geometric segments: a linear slide in at an angle of approximately 11°, a horizontal drag across, and a circular arc out. The tip entered the soil at a tip x-position of about 1.55 m and exited at about 0.79 m. The horizontal drag and circular arc out began at tip x-positions of 1.27 and 1.08 m, respectively. This trajectory was conducted at tip velocities of 1, 2, and 3 cm/s in air to establish the transducer tare and then in GRC-3b. To compare changes in force between static and ultrasonic tools, the bucket was tested with and without vibrations applied to the leading edge. Tool forces are evaluated at the 6-axis force and torque transducer between the bucket and the end of the robotic arm as well as kinematically transformed to the tip of the bucket.

Results: Data collected during this test campaign show measurable differences, as seen in Figures 3 and 4, in force and torque magnitudes during digging when actively vibrating the leading edge, or tip, of the bucket. The datasets were tared with the average of all air digs to show only the digging forces and torques. The force magnitudes in Figure 3 are derived from force components at the native transducer frame and transformed into the tip reference frame. The torque magnitudes in Figure 4 are derived from torque components from the native transducer frame.

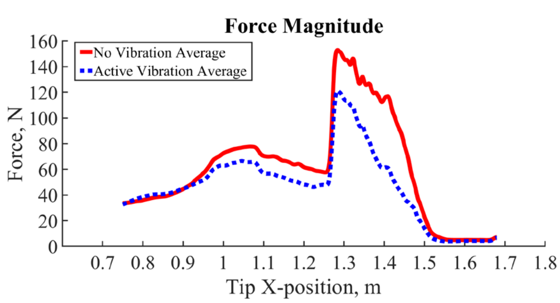

Figure 3. Average force magnitude curves transformed from forces at the bucket tip produced from datasets at all test speeds (1, 2, and 3 cm/s).

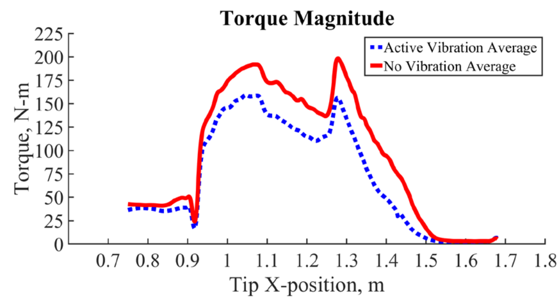

Figure 4. Average torque magnitude curves from measured transducer values produced from datasets at all test speeds (1, 2, and 3 cm/s).

Discussion: This study represents the first formal implementation of an ultrasonic leading edge into an excavation bucket of useful scale. The data show that force and torque reduction are dependent on trajectory geometry and vibration usage. The concept of an ultrasonic leading edge should not be considered specific to bucket applications and may provide benefit for other blade tillage tools. The results from this test campaign show potential for a new class of vibration assisted excavation tools that have many possible optimization parameters including but not limited to frequency, amplitude, trajectory geometry, and tip speed.

References:

[1] NASA, "NASA's Lunar Exploration Program Overview," no. September, p. 74, 2020, [Online] Available:https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf. [2] W. D. Carrier, "Grain Size Distribution," *Apollo Int. Mag. Art Antiq.*, vol. 6, pp. 250–263, 1973. [3] "Apollo Program Summary Report," 1975. [4] E. Rezich, K. Harrigan, F. Thomas, and D. Ludwiczak, "Ultrasonically Assisted Blade Technologies for Lunar Excavation," 2021. [5] M. P. Proctor and F. Thomas, "Power Measurements to Excavate Lunar Soil Simulant GRC-3B Using Arc Backhoe Trajectories," ASCE Earth and Space 2022, 18th Biennial International Conference. [6] M. P. Proctor, et al, "Force Measurements to Excavate Lightly Compacted Granular Lunar Soil Simulant GRC-3B," ASCE Earth and Space Conference, April 2021. [7] M. P. Proctor, "Experimental Facility to Measure Power and Forces to Excavate Lunar Regolith Simulants," Tenth Joint Meeting of the Space Resources Roundtable and the Planetary & Terrestrial Mining Sciences Symposium, June 2019.