Regolith Flow Mitigation and Control in Reduced Gravity via Vertically Vibrating Pocket Feeder

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Abstract

This paper discloses a method and system for achieving continuous and controllable flow of granular lunar regolith simulant under reduced gravity conditions, including 1/6th-g, by means of vertical vibration and mechanically rotated pocket feeder systems integrated beneath variable-draw-angle hoppers. The approach was successfully demonstrated during parabolic flight and may constitute the first publicly documented proof of sustained granular flow in true lunar gravity without clogging. Though inspired by terrestrial powder handling, the integration and demonstrated performance under lunar gravity is novel and foundational to *In Situ* Resource Utilization (ISRU) feasibility [Walton et al., 2007].

1 Introduction

Material flow behavior in low-gravity environments is fundamentally distinct from Earth due to diminished driving forces in gravity flow systems [Walton, 2012], [Ramé et al., 2010]. Most ISRU concepts rely on the assumption that regolith can be delivered to processing units without arching and jamming. Our experiments challenge and resolve this assumption by validating a working hardware system in lunar gravity aboard parabolic flights.

2 Experimental Setup

Eight experimental configurations were tested using four reducer geometries (KF-16, KF-25, KF-40, KF-50), each repeated twice. Vertical vibration was applied at 43-65 Hz, vibration amplitudes were varied between flights, and pocket feeder RPM was varied. All experiments occurred in a sealed vacuum chamber aboard a parabolic aircraft simulating 1/6th-g. A geotechnical lunar highlands regolith simulant ICN-LHT-1 (comparable to CSM-LHT-1) was used in all experiments. Instrumentation included load cells for mass flow, accelerometers on the base plate and individual test articles, and visual camera recording.

3 Hardware System

The regolith feed system, designed for experimental studies, comprises eight feed systems, structured as four unique geometries duplicated once to total eight. Each system shares a hopper with a uniform size of KF-50 across all eight setups. However, the hopper end is fitted with a reducer

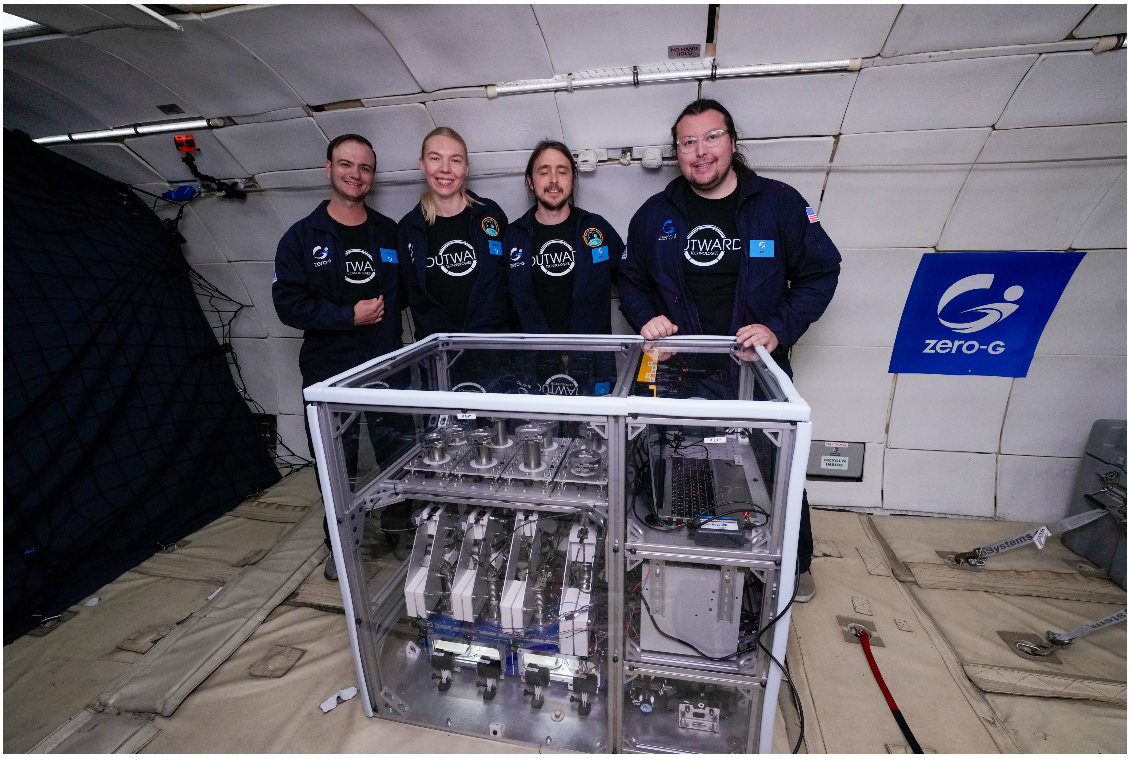

Figure 1: Payload and team during lunar parabolic flight.

to form a conical shape at the outlet, and these reducers vary in size—KF-16, KF-25, KF-40, and KF-50. By using different reducers, the system creates variations in both the hopper angle and the outlet size, enabling diverse flow characteristics for testing. Regolith exits the hopper through the reducer into a pocket feeder, driven by a pocket feeder motor, which meters the material using rotating pockets. The regolith then flows into a tube, mounted to a vacuum chamber, directing the material to a transparent acrylic box inside the chamber. A load cell beneath the box's base monitors the mass flow in real time. A vibration motor, mounted on a bracket around the hopper, introduces vibrational frequency and amplitude as adjustable parameters to prevent clogging and ensure consistent flow. An accelerometer on the same bracket monitors these vibration parameters for system optimization. Vibration isolators included to minimize unwanted vibration transmission, ensuring stability and changing the amplitude when needed. The vacuum chamber features glass windows for viewing the transparent acrylic box where regolith drops, with a GoPro camera positioned opposite the window to record the flow for visual analysis. Figure 2 shows one of the configurations, where hopper (KF-50) is connected to the cross tee (KF-16) via a reducer.

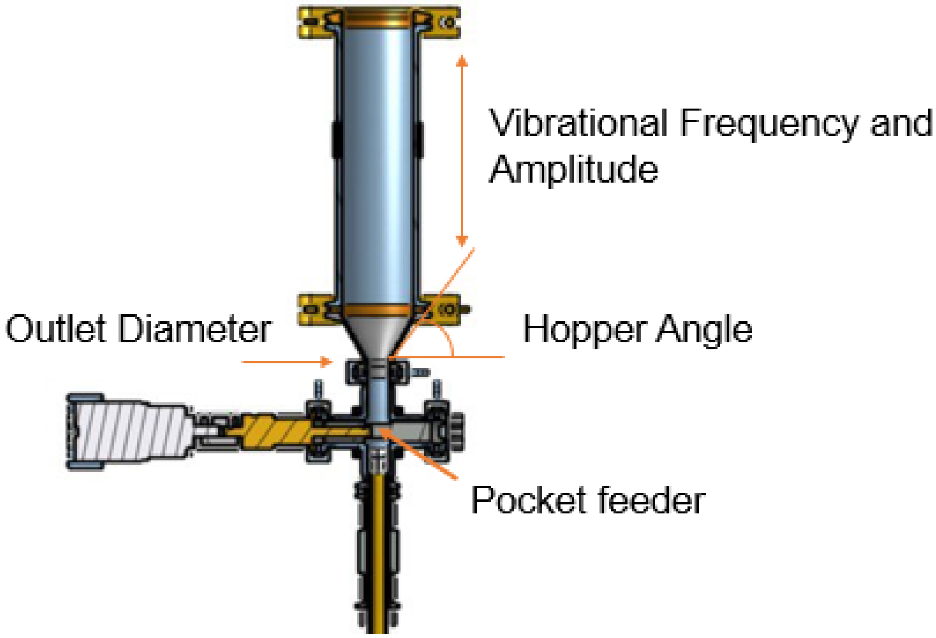

Figure 2: Cross-sectional diagram of prototype and components.

4 Granular Flow Mechanism

Without vibration, friction and cohesion lead to arching and jamming. Under vertical vibration, particle-particle and particle-wall interactions are dynamically interrupted, restoring flow. The current understanding from these experiments is that when vertical acceleration exceeds gravitational accelerations, the force chains that enable stable arch structures within the granular media are disrupted, thereby leading to removal of blockages and greatly enhanced flow characteristics when vibration with sufficient vertical accelerations is applied.

5 Results

Experimental results showed robust flow when active mitigation (vibration + rotation) was engaged. All geometries jammed when no vibration was applied. Figure 4 shows acceleration waveforms from Flight 1 and 2 for KF-16 size configuration. Table 1 and Table 2 shows load cell data analysis for KF-16 from Flight 1 and 2. Parabolas with anomalies were excluded from the calculation of the mean and standard deviation for each condition.

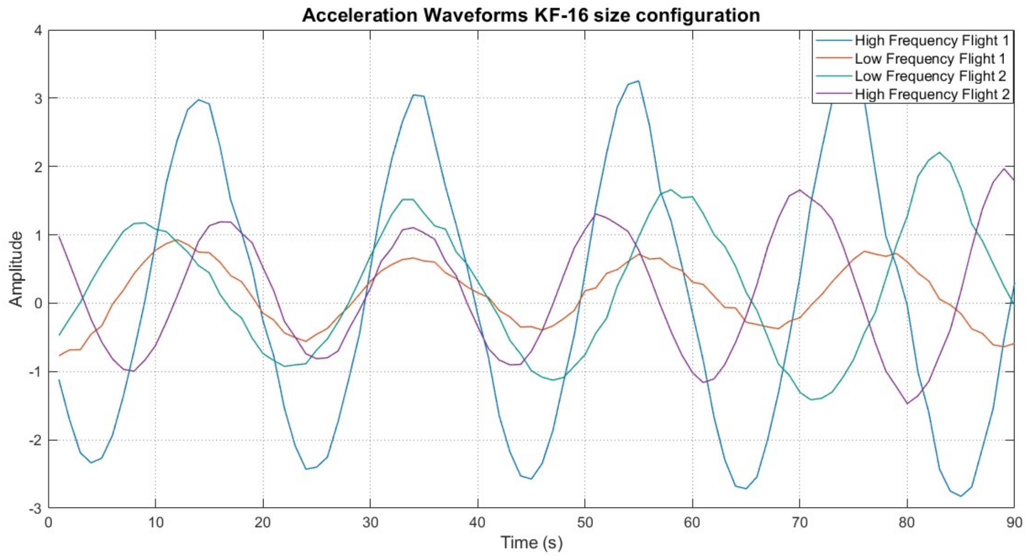

Figure 3: Acceleration input waveforms during tests.

Table 1: Flight 1 flow outcomes of KF-16 configuration across vibration and motor states (1/6g, 25 seconds of flow).

Condition	Amplitude	Mean [g]	Std Dev [g]	Mass Flow Rate [g/s]
High Frequency, High RPM	Low	19.4	9.44	0.78
Low Frequency, High RPM	Low	11.48	5.79	0.46
High Frequency, Low RPM	Low	18.73	3.78	0.75
Low Frequency, Low RPM	Low	7.75	4.48	0.31

Table 2: Flight 2 flow outcomes of KF-16 configuration across vibration and motor states (1/6g, 18 seconds of flow).

Condition	Amplitude	Mean [g]	Std Dev [g]	Mass Flow Rate [g/s]
High Frequency, High RPM	High	14.13	6.51	0.78
Low Frequency, High RPM	High	7.87	7.01	0.44
High Frequency, Low RPM	High	11.83	8.65	0.66
Low Frequency, Low RPM	High	10.46	6.47	0.58

6 Flow Condition Matrix

Table 3: Flow outcomes across geometric configurations and vibration states (1/6g).

Condition	**KF16**	**KF25**	**KF40**	**KF50**
Vibration On, Rotation On	Flow	Flow	Flow	Flow
Vibration Off, Rotation On	No Flow	No Flow	No Flow	No Flow
Vibration On, Rotation Off	No Flow	No Flow	No Flow	No Flow
Vibration Off, Rotation Off	No Flow	No Flow	No Flow	No Flow

7 Conclusion

This experiment demonstrates for the first time that controlled regolith flow in lunar gravity is achievable using common industrial mechanisms adapted to the lunar context. The validated combination of vertical vibration and pocket feeding removes a longstanding bottleneck in ISRU system integration by enabling continuous and controllable flow from lunar regolith hoppers and related granular transport equipment [Reiss et al., 2014]. This approach removes a critical barrier to continuous excavation and processing for lunar ISRU, enabling hopper-fed reactors, oxygen extraction, and construction systems.

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8 Appendix A

Table 4: Flight 1 Matrix of Flow Condition Detailing Parabola Condition (PC), Flow (F), No Flow (NF), Reduced Flow (RF), and Intermittent Flow (IF)

PC	Vib	Amp	G	Freq	RPM	1	2	3	4	5	6	7	8
1	On	Low	1/6	High	High	F	F	F	F	F	F	F	F
2	Off	Low	1/6	Off	High	NF	IF	RF	NF	NF	RF	IF	RF
3	On	Low	1/6	Low	High	F	F	F	F	F	F	F	F
4	On	Low	1/6	Low	High	F	F	F	F	F	F	F	F
5	On	Low	1/6	High	Low	F	F	F	F	F	F	F	F
6	On	Low	1/6	Low	Low	F	F	F	F	F	F	F	F
7	Off	Low	1/6	Off	Low	RF	IF	IF	NF	NF	RF	IF	IF
8	On	Low	1/6	Low	Low	F	F	F	F	F	F	F	F
9	Off	Low	1/6	Off	High	NF	NF	IF	NF	NF	RF	IF	RF
10	On	Low	1/6	High	High	F	F	F	F	F	F	F	F
11	On	Low	1/6	Low	High	F	F	F	F	F	F	F	F
12	On	Low	1/6	High	High	F	F	F	F	F	F	F	F
13	On	Low	1/6	High	Low	F	F	F	F	F	F	F	F
14	Off	Low	1/6	Off	Low	NF	NF	IF	NF	NF	NF	IF	IF
15	Off	Low	1/6	Off	High	RF	IF	RF	NF	NF	RF	IF	IF
16	On	Low	1/6	High	High	F	F	F	F	F	F	F	F
17	On	Low	1/6	Low	Low	F	F	F	F	F	F	F	F
18	Off	Low	1/6	Off	Low	NF	IF	IF	NF	NF	NF	RF	IF
19	On	Low	1/6	High	Low	F	F	F	F	F	F	F	F
20	On	Low	1/6	Low	Low	F	F	F	F	F	F	F	F
21	On	Low	1/6	High	Low	F	F	F	F	F	F	F	F
22	On	Low	1/6	Low	High	F	F	F	F	F	F	F	F
23	On	Low	1/6	High	Low	F	F	F	F	F	F	F	F
24	On	Low	1/6	High	High	F	F	F	F	F	F	F	F
25	On	Low	1/6	High	High	F	F	F	F	F	F	F	F
26	On	Low	1/6	Low	High	F	F	F	F	F	F	F	F
27	On	Low	1/6	Low	Low	F	F	F	F	F	F	F	F
28	On	Low	1/6	Low	Low	F	F	F	F	F	F	F	F
29	On	Low	1/6	High	Low	F	F	F	F	F	F	F	F
29	On	Low	2	High	Low	F	F	F	F	F	F	F	F
30	On	Low	1/6	Low	High	F	F	F	F	F	F	F	F
31	On	Low	1	High	High	F	F	F	F	F	F	F	F
32	Off	Low	1	Off	High	F	F	F	F	RF	F	RF	F
33	On	Low	1	Low	High	F	F	F	F	F	F	F	F
34	On	Low	1	High	Low	F	F	F	F	F	F	F	F
35	On	Low	1	Low	Low	F	F	F	F	F	F	F	F
36	Off	Low	1	Off	Low	RF	F	F	NF	RF	RF	RF	F

Table 5: Flight 2 Matrix of Flow Condition Detailing Parabola Condition (PC), Flow (F), No Flow (NF), Reduced Flow (RF), and Intermittent Flow (IF)

PC	**Vib**	**Amp**	**G**	**Freq**	**RPM**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	On	High	1/6	Low	Low	F	F	F	F	F	F	NF	F
2	On	High	1/6	High	Low	F	F	F	RF	F	F	NF	F
3	On	High	1/6	High	High	F	F	F	RF	F	F	NF	F
4	Off	High	1/6	Off	High	NF	RF	RF	NF	NF	RF	NF	RF
5	On	High	1/6	low	High	F	F	F	RF	F	F	NF	F
6	On	High	1/6	Low	Low	F	F	F	RF	F	F	NF	F
7	On	High	1/6	High	High	F	F	F	RF	F	F	NF	F
8	On	High	1/6	Low	High	F	F	F	RF	F	F	NF	F
9	On	High	1/6	High	Low	F	F	F	RF	F	F	NF	F
10	On	High	1/6	Low	Low	F	F	F	RF	F	F	NF	F
11	Off	High	1/6	Off	Low	NF	NF	IF	NF	NF	RF	NF	RF
12	On	High	1/6	High	Low	F	F	F	RF	F	F	NF	F
13	On	High	1/6	Low	High	F	F	F	RF	F	F	NF	F
14	On	High	1/6	High	High	F	F	F	RF	F	F	NF	F
15	On	High	1/6	Low	High	F	F	F	RF	F	F	NF	F
16	On	High	1/6	High	High	F	F	F	RF	F	F	NF	F
17	On	High	1/6	High	High	F	F	F	RF	F	F	NF	F
18	On	High	1/6	Low	Low	F	F	F	RF	F	F	NF	F
19	Off	High	1/6	Off	High	NF	NF	IF	NF	NF	NF	NF	F
20	On	High	1/6	High	Low	F	F	F	RF	F	F	NF	RF
20	On	High	2	High	Low	F	F	F	NF	F	F	NF	F
21	Off	High	1/6	Off	Low	F	F	IF	NF	F	IF	NF	RF
21	Off	High	1/6	Off	Low	NF	F	F	NF	F	F	NF	RF
22	On	High	2	Low	High	F	F	F	RF	F	F	NF	F
23	On	High	1/6	High	Low	F	F	F	RF	F	F	NF	F
23	On	High	2	High	Low	F	F	F	RF	F	F	NF	F
24	On	High	1/6	Low	Low	F	F	F	NF	F	F	NF	F
24	On	High	2	Low	Low	F	F	F	RF	F	F	NF	F
25	On	High	1/6	High	Low	F	F	F	RF	F	F	NF	F
25	On	High	2	High	Low	F	F	F	RF	F	F	NF	F
26	On	High	1/6	Low	High	F	F	F	RF	F	F	NF	F
26	On	High	2	Low	High	F	F	IF	NF	F	F	NF	F
27	On	High	1/6	High	High	F	F	F	RF	F	F	NF	F
28	On	High	1/6	Low	Low	F	F	F	F	F	F	NF	F
29	Off	High	1/6	Off	High	NF	RF	RF	NF	NF	RF	NF	NF
30	Off	High	1/6	Off	Low	NF	RF	RF	NF	NF	NF	NF	NF
31	On	High	1	High	High	F	F	F	NF	F	F	NF	E
32	Off	High	1	Off	High	RF	F	F	NF	F	F	NF	E
33	On	High	1	Low	High	F	F	F	RF	F	F	NF	E
34	On	High	1	High	Low	F	F	F	RF	F	F	NF	E
35	On	High	1	Low	Low	F	F	F	RF	F	F	NF	E
36	Off	High	1	Off	Low	RF	NF	RF	NF	RF	NF	NF	E