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In-Flight Investigation of Floating Beads for Sloshing Mitigation for Liquid-Fueled Rockets

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Abstract. Sloshing, characterized by free-surface wave formation in partially filled tanks under forced excitation, remains a major challenge in aerospace engineering, particularly for propellant tanks in launch vehicles. Laboratory studies have demonstrated that a granular layer placed at the liquid surface can significantly attenuate sloshing waves, provided that the granular medium remains compact. However, the performance of this mitigation strategy under real flight conditions has yet to be assessed. In this work, we investigate sloshing mitigation using a granular surface layer through an in-flight experiment conducted aboard a supersonic sounding rocket. The results show that granular surface damping is effective under realistic launch conditions as long as sufficient apparent gravity preserves the cohesion of the granular layer. Conversely, under near-microgravity conditions, loss of granular compactness leads to a breakdown of the damping mechanism. These findings indicate that granular-based sloshing mitigation is well suited for first-stage launch vehicles and sounding rockets, but is unlikely to remain effective during extended microgravity phases.

Introduction

Forced excitation of partially filled tanks induces sloshing, characterized by the formation of free-surface waves and the associated motion of the liquid [1, 2, 3]. In launch vehicles, this phenomenon constitutes a recurrent and critical challenge for liquid-propellant propulsion systems [2], where the dynamic interaction between the propellant, the structure, and the propulsion system can significantly affect vehicle stability and integrity. Sloshing-related dynamic couplings have contributed to documented launch vehicle anomalies [4].

Two major sloshing-induced mechanisms are of particular concern in this context. The first is the so-called pogo instability, a coupled fluid-structure-propulsion phenomenon arising from the interaction between propellant dynamics, structural compliance, and the propulsion system [5, 6]. During flight, propellant motion and system compliance generate pressure oscillations in the feed lines, leading to fluctuations in engine mass flow rate and thrust [5, 6]. These thrust oscillations excite structural vibrations of the launcher, which can in turn amplify the motion of the propellant within the tanks. When this feedback loop becomes unstable, it may result in severe structural damage or catastrophic failure of the vehicle. The second mechanism originates from the unsteady lateral forces and torques induced by sloshing. These loads can degrade attitude control performance, alter the vehicle trajectory, and ultimately compromise mission success, particularly during phases involving high acceleration or rapid changes in flight conditions [7, 8].

As a result, mitigating propellant sloshing in launch vehicles has long been recognized as a fundamental fluid-structure interaction problem in aerospace engineering, with strong parallels in aeronautics, naval engineering, and liquid transport industries [2, 7]. Most existing mitigation strategies rely on structural modifications of the tanks, such as baffles or internal appendages [3, 9]. While effective, these passive solutions increase structural complexity, incur a non-negligible mass penalty, and offer limited adaptability to varying fill levels and flight conditions.

Alternative approaches have been proposed based on the observation that the upper region of the liquid column accounts for the dominant contribution to sloshing-induced energy dissipation. These include the addition of a secondary liquid layer atop the primary fluid [10] or the use of foam-based damping methods [11, 12]. However, such strategies are generally incompatible with operational space vehicle propellant tanks, where strict preservation of fuel chemical purity is required. Introducing additional liquid phases or foam would induce miscibility and emulsion phenomena, potentially altering the thermophysical properties of the propellant and compromising propulsion system reliability.

In this context, the use of a floating solid granular layer represents a promising alternative, as it simultaneously preserves chemical purity and introduces a minimal mass penalty. Several laboratory studies have demonstrated that adding a layer of floating granular material on the free surface of a liquid can significantly attenuate sloshing [11, 12, 13, 14]. However, the effectiveness of this approach under realistic launch and flight conditions has not yet been demonstrated.

In this paper, we investigate the feasibility of granular surface damping through an in-flight experiment conducted aboard a supersonic sounding rocket. A layer of polystyrene beads was placed on the free surface of a liquid and integrated, along with a control experiment, into the payload of the EPFL Rocket Team's *Wildhorn* rocket, launched during the European Rocketry Challenge (EuRoC) in October 2022. The influence of the granular layer is examined during both the propulsion phase and the subsequent free-flight phase of the sounding rocket.

Physical Mechanisms of Propellant Sloshing and Damping Using Granular Media

Sloshing excitation mechanisms in launch vehicles. In launch vehicles, the excitation of propellant tanks arises primarily from vibrations transmitted through the base of the structure [2, 6]. During powered flight, thrust oscillations and pressure fluctuations generated by the propulsion system induce predominantly longitudinal vibrations of the launcher, which are directly transmitted to the tanks [5]. These axial excitations act mainly in the vertical direction and can favor the development of vertically forced sloshing, including Faraday-type instabilities at the liquid free surface under suitable parametric excitation conditions [14]. Such vertically induced excitations are commonly associated with engine dynamics and fluid-structure coupling phenomena, including the pogo effect, and constitute a major source of sloshing during propulsion phases [5, 6].

In addition to axial excitations, propellant tanks may also experience lateral forcing. Lateral sloshing can originate from aerodynamic loads, guidance and control maneuvers, structural bending modes, or external perturbations such as wind gusts and staging events [2, 7]. These transverse excitations primarily induce side-to-side liquid motion and lead to classical lateral sloshing modes [7]. However, compared to axial excitations, they are generally of secondary importance during nominal propulsion phases and tend to occur intermittently or under specific flight conditions [2].

Damping of Faraday waves using a granular surface layer. Under vertical periodic excitation, free-surface instabilities such as Faraday waves may develop and contribute significantly to sloshing-induced loads [7]. Previous laboratory studies have demonstrated that the presence of a floating granular layer at the liquid surface can lead to a strong attenuation, and in some regimes a near-complete suppression, of these instabilities, provided that the granular medium remains compact and continuous [14].

When the beads form a coherent layer, the granular medium behaves as an effective surface damper that strongly limits free-surface motion. In this regime, sloshing waves are either fully suppressed or reduced to negligible amplitudes. In contrast, when the excitation amplitude becomes sufficiently large to disrupt the cohesion of the bead layer, gaps may form at the surface. Faraday waves can then nucleate locally within these uncovered regions and rapidly propagate across the free surface, leading to a sharp loss of damping efficiency [14]. This mechanism, illustrated in figure 1, highlights the central role of granular layer continuity in sloshing mitigation.

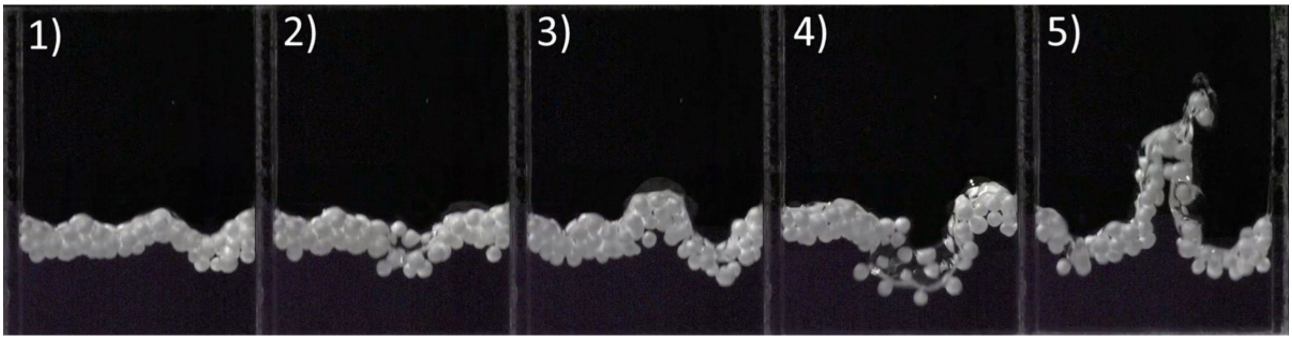

Fig. 1: Photo series of isopropanol Faraday wave with two layers of beads at (9.000 ± 0.005) Hz in a rectangular tank of dimensions $L = 70$ mm and $l = 15$ mm filled with liquid at rest at $h_{liq} = (32 \pm 2)$ mm which illustrates the phenomenon of continuity break of the bead block.[14]

Maintaining the coherence of the granular layer is therefore a key requirement for effective sloshing attenuation. Experimental observations indicate that this can be achieved by increasing the number of bead layers, ensuring that local discontinuities are rapidly filled and that the granular layer remains compact even under strong excitation [14].

Damping of lateral sloshing using a granular surface layer. Previous studies have shown that the presence of a floating granular layer at the liquid surface can also mitigate laterally induced sloshing [12]. The granular medium introduces additional dissipation mechanisms at the free surface, leading to a reduction in wave amplitude compared to the case without beads [12]. However, unlike vertically excited instabilities, lateral sloshing modes are not completely suppressed by the granular layer. Residual oscillations persist, as lateral forcing primarily excites bulk liquid motion rather than surface-dominated instabilities, which limits the effectiveness of surface-based damping strategies [2, 3, 7].

Experimental Setup

Rocket and flight phases. The experiment was embedded within the payload of the EPFL Rocket Team's *Wildhorn* sounding rocket, launched in October 2022 during the European Rocketry Challenge (EuRoC). The vehicle follows a conventional sounding-rocket flight profile, composed of an initial powered ascent phase followed by a ballistic free-flight phase after motor burnout.

The propulsion phase extends from lift-off to motor burnout and is characterized by intense axial accelerations and broadband vibratory loads transmitted through the rocket structure. These vibrations are predominantly induced by the solid rocket motor and arise from thrust oscillations, combustion instabilities, and pressure fluctuations within the motor chamber [6, 5]. Such excitation constitutes the dominant forcing mechanism acting on the payload during powered ascent. Comparable vibration environments have been extensively documented for sounding rockets of similar scale and propulsion architecture, where longitudinal excitation has been shown to strongly influence fluid motion and sloshing dynamics in onboard tanks and containers [1, 2, 3, 7].

Following motor burnout, the rocket transitions into a supersonic ballistic free-flight phase. During this regime, propulsion-induced vibrations rapidly decrease, and the dominant external excitations originate from aerodynamic loads, unsteady pressure distributions, and structural-aerodynamic interactions with the surrounding flow [15]. Concurrently, the apparent gravity level experienced by the payload progressively decreases along the ballistic trajectory, approaching near-microgravity conditions in the vicinity of apogee [16].

Experimental payload. The sloshing experiment was integrated at the top of the rocket payload and implemented using a modular CanSat-based architecture [17]. This configuration ensures that any observed difference in sloshing behavior can be directly attributed to the presence of the granular layer. A three-dimensional CAD model of the experimental setup is shown in figure 2.

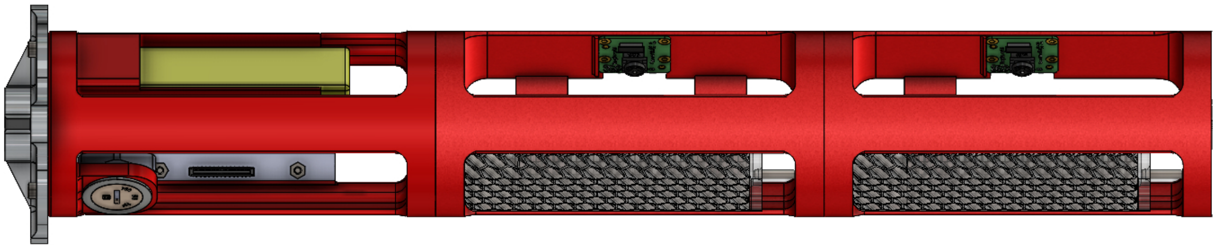

Fig. 2: Three-dimensional CAD model of the experimental payload, illustrating the modular CanSat-based architecture and the location of the sloshing reservoirs within the rocket.

Two identical CanSat units were dedicated to the sloshing experiments, each housing a transparent rectangular reservoir together with an optical acquisition system. The two reservoirs were strictly identical in geometry and instrumentation, allowing a direct comparison between a reference liquid configuration and a granular-damped configuration.

Each reservoir had internal dimensions of height $h = 80$ mm, width $L = 40$ mm, and length $l = 10$ mm, and was partially filled with isopropanol. Uniform illumination of the free surface was ensured using integrated white LEDs, while engraved reference markings on the reservoir walls provided a spatial calibration for quantitative measurements of the free-surface elevation. Representative pictures of the liquid free surface, with and without the presence of polystyrene beads, are shown in figure 3.

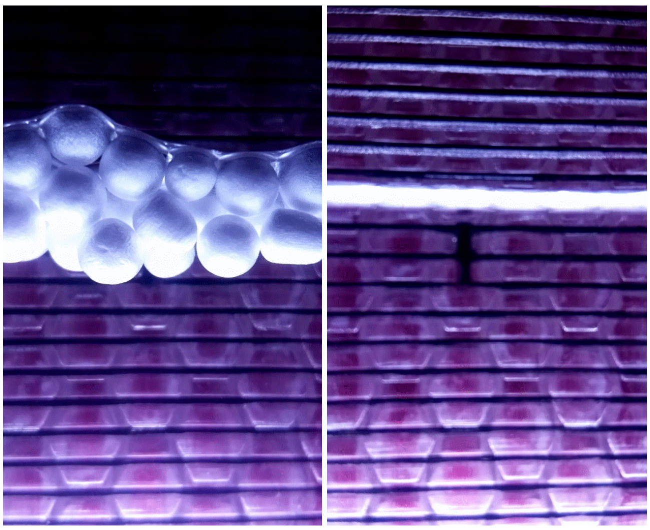

Fig. 3: Two pictures of the liquid with and without beads in the experiment at rest.

The free-surface dynamics were recorded using miniature CMOS cameras (Sony IMX219), operating at a resolution of 1920×1080 pixels and a frame rate of 30 fps. Each camera was rigidly mounted with respect to its corresponding reservoir, ensuring the absence of relative motion between the imaging system and the fluid container throughout the flight.

A third CanSat unit housed the central data acquisition and control system. It included a Raspberry Pi 4 computing unit interfaced with both cameras, as well as an inertial and environmental sensing suite. A three-axis accelerometer (ADXL345) was used to measure the acceleration levels experienced by the payload, while a barometric pressure sensor (BMP390) provided pressure and altitude data.

These measurements were used to correlate the observed sloshing dynamics with the different flight phases and to estimate the apparent gravity level inside the rocket.

The granular medium consisted of spherical polystyrene beads, with diameters ranging from 0.3 to 0.6 cm. The beads were identical to those used in the laboratory experiments reported in this study [14].

Image processing. Sloshing dynamics were quantified using image processing techniques applied to the video recordings obtained during flight.

For each recorded video frame, the position of the liquid free surface was extracted using a custom image-processing algorithm. The interface between the liquid and air, or between the liquid and the polystyrene beads, was detected based on light contrast gradients and contrast differences between the illuminated fluid region and its surroundings. Once identified, the free-surface profile was reconstructed along the longitudinal direction of the reservoir.

From this reconstructed profile, key geometric quantities are extracted, including the maximum and minimum surface elevations. These quantities allow the determination of the instantaneous sloshing amplitude as a function of time.

During the free-flight phase, the reduction of apparent gravity leads to a progressive loss of surface coherence, making classical free-surface detection more challenging. In this regime, the analysis focuses primarily on qualitative observations of granular layer cohesion and on comparisons between the behaviors observed during the propulsion and free-flight phases.

Results

Propulsion phase. The propulsion phase corresponds to the first 10 seconds of flight and is characterized by two successive acceleration regimes. An initial phase of high axial acceleration, reaching approximately $9\,g$, occurs during the first 3 seconds after lift-off, followed by a phase of lower and quasi-steady acceleration of about $2\,g$ lasting for the remaining 7 seconds.

During the initial high-acceleration period, the reservoir containing only liquid exhibited the rapid development of large-amplitude surface waves, indicative of a resonant sloshing response. In contrast, no significant wave motion was observed in the reservoir containing polystyrene beads during this period. Throughout the subsequent lower-acceleration phase, the liquid-only reservoir continued to display pronounced free-surface oscillations, whereas the reservoir with beads remained free of observable wave activity.

Overall, no sloshing motion was detected in the bead-filled reservoir during the entire propulsion phase, while significant free-surface oscillations were consistently observed in the reference reservoir without beads. The temporal evolution of the measured wave amplitude for both configurations during the propulsion phase is shown in figure 4.

Free-flight phase. The free-flight phase starts approximately 10 seconds after launch and corresponds to a near-zero apparent gravity environment. During this phase, the granular medium in the bead-filled reservoir progressively loses its compact structure and becomes disorganized. As a result, no damping of the liquid motion is observed in this configuration.

Visual observations indicate that the beads no longer form a coherent layer during free flight, leading to the disappearance of the sloshing attenuation previously observed during the propulsion phase. A representative image of the reservoir containing beads during the free-flight phase is shown in figure 5.

Discussion

The in-flight experiment reported in this study provides a direct assessment of granular-based sloshing mitigation under realistic launch conditions, bridging the gap between laboratory experiments and actual rocket environments. A clear contrast is observed between the propulsion and free-flight phases, emphasizing the central role of apparent gravity in governing the effectiveness of granular surface damping.

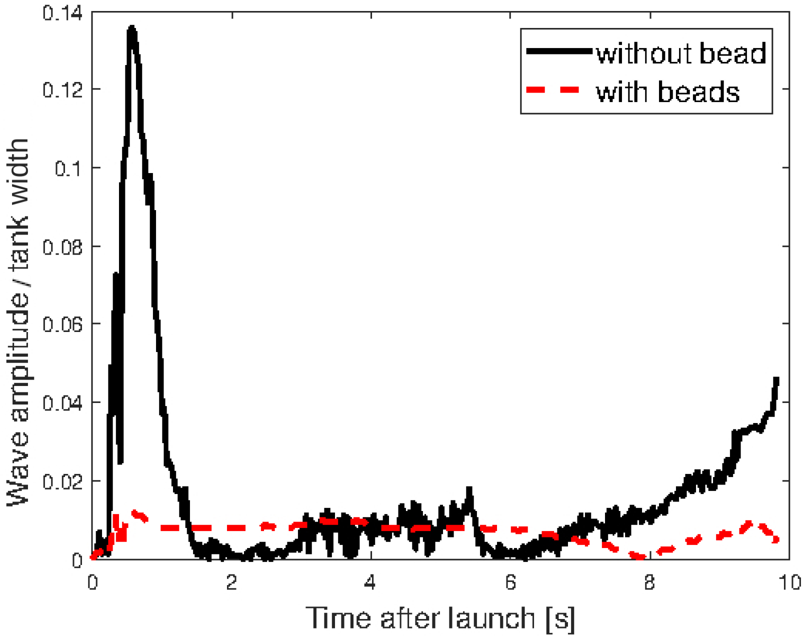

Fig. 4: Temporal evolution of the normalized free-surface wave amplitude during the propulsion phase for the reservoirs with and without polystyrene beads.

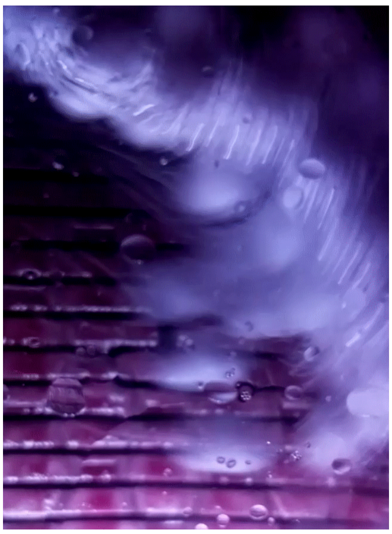

Fig. 5: Representative image of the reservoir containing polystyrene beads during the free-flight phase, showing the loss of bead compactness under near-zero gravity conditions.

During the propulsion phase, characterized by sustained axial acceleration and strong longitudinal vibratory forcing, the granular layer remains compact and coherent at the liquid free surface. Under these conditions, the bead-filled reservoir exhibits a complete suppression of observable sloshing motion, while the reference configuration without beads develops large-amplitude free-surface oscillations. This behavior is consistent with previous laboratory studies and confirms that the damping mechanisms identified under controlled conditions remain effective under realistic launch vibration spectra and acceleration levels.

The observed damping during propulsion can be attributed to the preservation of granular layer cohesion. Sustained apparent gravity provides enough normal loading to maintain contact between the beads and a continuous granular layer, which constrains free-surface deformation and introduces additional dissipation at the interface. The absence of observable sloshing throughout both high and moderate acceleration regimes indicates that the mechanism is robust over a wide range of accelerations.

In contrast, the free-flight phase reveals a fundamental limitation of granular surface damping. As the apparent gravity level decreases toward near-zero, the granular layer progressively loses its compact structure and becomes disorganized, preventing the formation of a continuous surface layer. Under these conditions, the granular medium no longer constrains the free surface and sloshing attenuation breaks down. This observation is consistent with laboratory results showing that granular damping critically depends on layer continuity and cohesion.

These results demonstrate that granular surface damping is inherently apparent gravity dependent. While highly effective during propulsion phases with sustained acceleration, the approach is not suitable for extended microgravity environments. From an application perspective, granular-based damping is therefore well suited for launch vehicle first stages and sounding rockets, where sloshing-induced loads are most critical, but is unlikely to remain effective during upper-stage coast phases or long-duration microgravity missions.

Conclusion

This study demonstrates that a floating granular surface layer can effectively mitigate liquid sloshing under realistic rocket launch conditions. In-flight measurements show that granular damping remains robust during the propulsion phase, where sustained axial acceleration preserves the cohesion of the granular layer and suppresses free-surface motion. In contrast, during the free-flight phase, the loss of apparent gravity leads to granular layer disorganization and a breakdown of the damping mechanism. These results indicate that granular-based sloshing mitigation is inherently gravity-dependent and is therefore well suited for applications involving sustained acceleration, such as launch vehicle first stages and sounding rockets. Conversely, the approach is not expected to remain effective during extended microgravity or ballistic phases, where alternative mitigation strategies must be considered.

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