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1 Abstract

This conceptual design report presents an innovative water rocket featuring winged surfaces to enhance aerodynamic performance, deviating from traditional torpedo-shaped designs. The propellant chamber utilizes a slightly convex, perforated cylinder integrated with 3D-printed internal baffles to mitigate sloshing effects. A manual pump pressurizes the chamber, with a cable-tie release mechanism enabling launch initiation. To evaluate sloshing dynamics, two methodologies were employed: Computational fluid dynamics (**CFD**) analysis for fluid-structure interaction and **Monte Carlo** simulations to assess uncertainty and optimize design parameters. The FEM results informed structural adjustments, while stochastic modeling guided risk mitigation strategies. This dual approach ensured a robust preliminary design, balancing innovation with functional reliability.
The findings underscore the viability of non-traditional geometries and computational methods in sloshing suppression, providing a foundation for further refinement in the final design phase.

2 Introduction

Liquid sloshing in partially filled propellant tanks poses a lot of challenges in aerospace engineering, affecting structural integrity and also flight stability. During dynamic phases such as launch, sloshing induces impact pressures on tank walls, destabilizes vehicle orientation, and compromises propulsion performance [1]. Traditional mitigation strategies, such as rigid baffles, often add excessive weight or fail under nonlinear fluid behavior, necessitating innovative solutions. Recent advancements in computational fluid dynamics, including Smoothed Particle Hydrodynamics (SPH) and Reynolds-averaged Navier-Stokes (RANS) simulations, have enabled precise modeling of sloshing dynamics [2] [3]. However, aerospace applications demand lightweight, adaptive systems that balance suppression efficacy with minimal mass penalties.
Drawing inspiration from non-aerospace domains, this project integrates two key innovations: **3D-printed perforated baffles** and dual computational methodologies. The baffle design, inspired by maritime anti-sloshing systems, utilizes a convex, perforated chamber to disrupt wave formation while minimizing weight. Additionally, stochastic **Monte Carlo simulations**, traditionally employed in risk assessment and financial modeling, are adapted to quantify uncertainty in sloshing behavior under variable flight conditions. Furthermore, we have evaluated the innovative idea of using Porous Materials (Sponges) to dampen sloshing and stabilize the CoG.

3 Project Organisation

	Role
[redacted]	Team leader, Launcher, release mechanism
[redacted]	Release mechanism, safety manager
[redacted]	Aerodynamics
[redacted]	Aerodynamics, Chambers
[redacted]	Aerodynamics
[redacted]	Chambers

Table 1: Team roles

It is worth noting that ***all*** members of the team contributed significantly to the study of chambers.

For an additional layer of organization, we implemented a Gantt chart

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Figure 1: Gantt chart

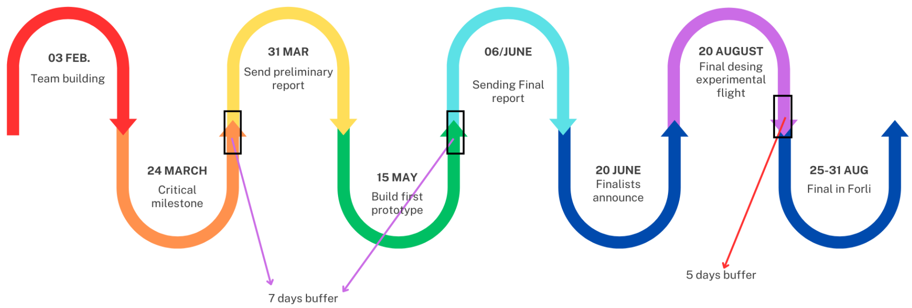

Figure 2: Project timeline

Risk Management

- **Time Buffers:** 7-day buffer before deadlines
- **Resource Redundancy:** Cross-trained members on critical subsystems
- **Acceleration Options:** Parallel CFD validation for multiple designs
- **Mitigation Protocols:** Weekly risk reviews with fallback configurations

For the detailed organization of the project, see the Gantt chart.

4 Requirements Capture

The primary objective is to maximize the flight score while maintaining all construction and flight phases in **maximum safety** (1)

$$F.S = (\sqrt{H.D.(m)^2 + Altitude(m)^2} + Time(s)) \times \frac{Payload(kg)}{TakeoffWeight(kg)} \quad (1)$$

Where:

- F.S = flight score
- H.D = Horizontal distance

Req ID	Shall Statement	Verification Criteria
RQ-01	[redacted]	[redacted]
RQ-02	[redacted]	[redacted]
RQ-03	[redacted]	[redacted]
RQ-04	[redacted]	[redacted]
RQ-05	[redacted]	[redacted]
RQ-06	[redacted]	[redacted]
RQ-07	[redacted]	[redacted]
RQ-08	[redacted]	[redacted]
RQ-09	[redacted]	[redacted]
RQ-10	[redacted]	[redacted]
RQ-11	[redacted]	[redacted]
RQ-12	[redacted]	[redacted]
RQ-13	[redacted]	[redacted]
RQ-14	[redacted]	[redacted]
RQ-15	[redacted]	[redacted]
RQ-16	[redacted]	[redacted]

Table 2: List of requirements

5 Concept Investigation

In this preliminary phase, four distinct design concepts were explored.

5.1 Sloshing Tank Design

Our initial slosher design adopts an hourglass inspired shape with a perforated midsection—essentially a long donut in an asymmetrical hourglass form 4. The design narrows toward the front to limit liquid migration that could shift the center of gravity (CoG) excessively forward and make canard during pitch control inefficient to fullfill RQ-07 , RQ-09. Inside the slosher, additional baffles (RQ-11) help dampen liquid motion during rapid attitude changes, such as the transition from vertical ascent to glide (RQ-10, RQ-11). The slosher is designed to be longer than it is wide, addressing the challenge of mitigating roll instability (which is generally harder to control than pitch, especially with a canard-only control system (RQ-12)). Additionally, the integration of porous materials (sponges) within the slosher is being considered to further dampen oscillations and stabilize the CoG.

5.2 Design Concepts

5.2.1 Design 1: Canard with Detachable Propulsion Tank

- **Aerodynamics & Stability:** High-wing configuration with tapered wings (no negative dihedral) enhances roll stability. The canard improves pitch stability during glide.
- **Control:** Canard and vertical stabilizers ensure effective directional control.
- **Structural Integrity & Propulsion:** A detachable propulsion chamber mounted below the vehicle reduces mass post-burnout and allows better positioning of the slosher.
- **Key Challenge:** Optimizing the slosher design and detachment mechanism to maintain stability.

5.2.2 Design 2: Canard with Integrated Propulsion

- **Aerodynamics & Stability:** Canard configuration with a positive dihedral, low-mounted main wing provides enhanced stability.
- **Control:** Vertical stabilizers and canard deliver robust control.
- **Structural Integrity & Propulsion:** Fixed rear propulsion chamber housed in an expandable tube avoids detachment issues, paired with a shorter, wider slosher.
- **Key Challenge:** Evaluating the influence of the shorter but wider slosher tank on dynamic stability.

5.2.3 Design 3: Canard with Triple Propulsion Chambers

- **Aerodynamics & Stability:** Similar canard configuration with main wings positioned near three propulsion chambers; absence of vertical stabilizers raises concerns over yaw stability.
- **Control:** Canard aids in pitch control, but asymmetric thrust may occur.
- **Structural Integrity & Propulsion:** Triple propulsion chambers allow thrust modulation and redundancy, yet add complexity.
- **Key Challenge:** Achieving uniform thrust distribution and managing potential asymmetric loads.

5.2.4 Design 4: Traditional Configuration with Enclosing Slosher

- **Aerodynamics & Stability:** Conventional tail-plane setup with wings mounted above the CoG provides natural stability; central vertical stabilizer enhances directional control.
- **Control:** Traditional aerodynamic surfaces govern the vehicle.
- **Structural Integrity & Propulsion:** Single propulsion chamber encased within an expansive slosher that fully surrounds it, allowing space for expansion.
- **Key Challenge:** Analyzing the large slosher's influence on dynamic behavior and ensuring proper protection/insulation for the propulsion chamber.

5.3 Innovations & Further Analysis

Innovative measures include:

- Porous Materials (Sponges): To dampen sloshing and stabilize the CoG
- Baffle Designs: Inspired by marine/automotive systems for additional fluid control
- Detachable Chamber: Reduces unnecessary mass and drag, enhancing stability
- Monte Carlo Simulation: For predicting fluid movement and enhancing design robustness

Areas for Further Analysis:

- Effectiveness of sponges in sloshing reduction
- Asymmetric thrust effects in Design 3
- CoG sensitivity and detachment dynamics in Design 1
- Optimization of slosher configuration (e.g., additional baffles/grooves)
- CoG variation effects on flight dynamics through simulations

5.4 Concept investigation diagrams

[redacted]

(a) Design 1

[redacted]

(b) Design 3

[redacted]

(c) Design 2

[redacted]

(d) Design 4

Figure 3: Design concepts analysis

6 Concept Justification

The QFD analysis highlights key performance criteria for each design, with differences in implementation and technical solutions defining their strengths and weaknesses. Below is an evaluation of how each design meets the outlined requirements based on the requirements present in the FMA.

In order to "incorporate a means of controlling the descent of the vector" a glider with a Canard configuration and tapered wings was chosen for each proposed design.

This configuration maximises flight time and distance travelled since they decrease the trim drag by helping manage the airflow of the wing during landing, increasing the value of the flight score formula.

For the center of gravity, (CoG), we used this formula with the nose of the plane being the reference point

[redacted] (2)

where:

- m_p: empty propulsion chamber mass;
- d_p: distance of propulsion chamber from the nose;
- m_w: wing mass;
- d_w: distance of wing fro the nose;
- m_s: sloshing tank mass;
- d_s: distance of sloshing tank from the nose

while we estimate the total thrust with as the rate of momentum during the mission time:

[redacted] (3)

Design Concept A

- **Propulsion**
  - + Simple manufacturing with a single propulsion chamber using cost-effective materials: materials resistant to mechanical fatigue can be used more easily when a single propulsion chamber is used;
  - + Lightweight structure optimizing the rocket's mass: the release of the stage makes the structure much lighter;
  - + High performance when properly designed and tested: the presence of stages allows to give optimal thrust at any point in time;
- **Aerodynamics**
  - + Generates lift effectively with properly dimensioned aerodynamic surfaces;
  - + Stable against sloshing with appropriate control mechanisms: the vertical empennage and the slosher being located between wing planes minimize sloshing;
  - + Lightweight and reliable with suitable material selection: the release of the stage makes the structure much lighter;
  - - *Limitation*: Requires precise control system for detachment at peak altitude. Infact, there can be stability problems due to the detachment of the first stage which causes both a change in CoG position and a disturbance due to the detachment
- **Launch System**
  - + Easy to manufacture with optimized material selection: the launcher is balanced due to the presence of only one propulsion chamber;
  - + Aerodynamic stability and structurally robust: the first stage can be set to a thrust optimal for takeoff improving stability

- **Release Mechanism**
  + High safety due to single-chamber pressurization, (not particularly susceptible to external variables due to its simplicity);
  + Reliability dependent on material choice, with strong materials reusable for multiple launches

Design Concept B

- **Propulsion**
  + Single-chamber design ensuring ease of fabrication and lightweight construction: the launcher is balanced due to the presence of one propulsion chamber, the lack of stages ensures ease of assembly;
  + High performance with accurate modelling: while the single stage doesn't grant maximum thrust both at takeoff and after, it can still be fairly high with a proper nozzle choice
- **Aerodynamics**
  + Stable splashdown behaviour through CoG control
  + Lightweight and structurally reliable: the drag is lowered by the simplicity of the configuration, the lack of stages allows the aircraft to remain stable more easily
- **Launch System**
  + Stability from optimized single-stage rocket shape
  + Strong structural integrity
- **Release System**
  + High safety and pressurization reliability

Design Concept C

- **Propulsion**
  + High performance if precisely synchronized: having 3 propulsion chambers greatly increases thrust efficiency and helps releasing propellant rapidly;
  - *Limitations*: Complex three-chamber system increases weight, manufacturing difficulty and makes maintaining pressure until launch harder
- **Aerodynamics**
  + Stability through CoG control but lacks optimized lift generation;
  - *Limitation*: Reduced aerodynamic stability

- **Launch System**
  - + Compact shape enhances rigidity;
  - - *Limitation*: Complex handling of multiple propulsion chambers
- **Release System**
  - - *Limitations*: Synchronization issues affect safety and reliability.

Design Concept D

- **Propulsion**
  - + Simple FTC tubing construction for lightweight and high-performance propulsion, (high thrust efficiency and helps with reusability and structural resistance)
- **Aerodynamics**
  - + Good lift generation due to FTC aerodynamic shape;
  - - *Limitation*: Stability issues due to elongated sloshing tank
- **Launch System**
  - + Easy manufacturing but requires structural testing;
- **Release System**
  - + Safe pressurization using FTC tubing

7 Preliminary Design Choice

Both the first and the second design fully meet the design requirement.The first design seems to be the most performing, thanks to the multistage configuration. However, this same configuration needs many tests to be optimized. The second design, although very similar to the first, is more reliable because is a single stage.

The third and fourth design, while being interesting case studies, fall short of expectations as they hardly comply RQ-03, RQ-14, RQ-03 and probably won't be used.That said, we have opted for Concept B, as we can see in Tab. (3): We also provide chamber's early-render:

Figure 4: chamber early desing view 1

Figure 5: chamber early desing view 2

Figure 6: chamber early desing view 3

Table 3: Pugh matrix

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8 Ap[redacted]

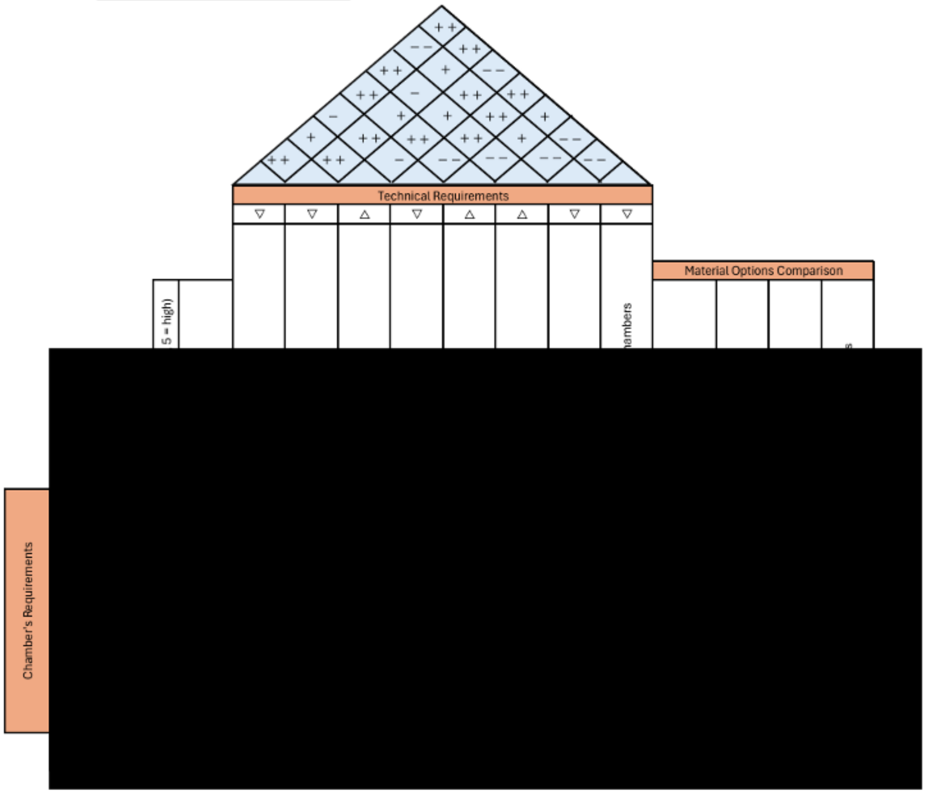

Figure 7: Chambers QFD

[redacted]

Figure 8: Aerodynamics QFD

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Figure 9: Launchers QFD

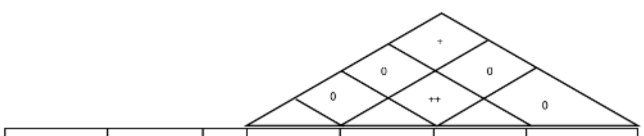

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Figure 10: Release mechanism QFD

Figure 11: Aerodynamics p-diagram

Figure 12: Chambers p-diagram

Figure 13: Sloshers p-diagram

Figure 14: Release p-diagram

References

[1] Y.G. Chen, K. Djidjeli, and W.G. Price. Numerical simulation of liquid sloshing phenomena in partially filled containers. *Computers & Fluids*, 38(4):830–842, 2009.

[2] L Delorme, A Souto Iglesias, and S Abril Pérez. Sloshing loads simulation in lng tankers with sph. In *International conference on computational methods in marine engineering*, pages 1–10, 2005.

[3] Ashkan Rafiee, Fabrizio Pistani, and Krish Thiagarajan. Study of liquid sloshing: numerical and experimental approach. *Computational Mechanics*, 47:65–75, 2011.