

PhD Proposal

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Multi-fidelity modeling of propellant sloshing in space launcher tanks through the hybridization of analytical models, CFD, and physics-informed neural networks.

Keywords

Propellant sloshing, space tanks, CFD, pendulum models, PINN, GNC simulation, ECSS/SMP

Desired Profile and Skills

- Engineering degree or Master's degree in aerospace or applied data science.
- Skills in fluid mechanics, numerical simulation (CFD), reduced-order modeling methods (mass-spring model, pendulum).
- Interest or experience in physics-informed machine learning (PINN, PIML).
- Proficiency in C++ and/or Python, familiarity with ECSS/SMP standards is a plus.

PhD Project Description

Physics-Informed Neural Network (PINN)s represent a new paradigm in deep learning, capable of solving both direct and inverse problems for nonlinear Partial Differential Equation (PDE)s [8]. By integrating underlying physical constraints into the architecture of a Feedforward Neural Network (FFNN), PINNs can be trained as surrogate models with little to no labeled data for inferring solutions to PDEs [3]. In the current literature, the implementation of PINN is seen both as a complement and a potential alternative to existing numerical techniques, across a wide range of research fields in science and engineering [6, 1, 2].

Context

The behavior of propellants in space launcher tanks directly impacts flight stability, the performance of flight control algorithms, and mission success. During propelled phases, the dynamic effects of sloshing masses can be efficiently modeled using equivalent pendulum models (see for example [4]), but these models become limited when the acceleration regime becomes too weak (and even non-functional in micro-gravity), the sloshing motion too large, or when dominant biphasic behavior occurs.

Problem

In a numerical simulation context, especially for flight control validation and qualification, it is essential to have models that are both accurate, fast, and adaptable, capable of representing physical phenomena at different scales and under various flight conditions. The current approaches struggle to provide a generic, fast, and reliable framework for modeling propellant sloshing during all flight phases. CFD provides accurate but costly results, reduced models (pendulums, mass-spring) are effective during powered phases with relatively small sloshing angles, while PINN offer a promising trade-off between accuracy and cost.

Objectives

This thesis aims to develop a generic framework for modeling propellant behavior in tanks, integrating multiple fidelity levels, and usable in standard industrial environments (fully numerical simulation or with physical elements), with a focus on cases where reduced models are unavailable (micro-gravity and launcher dynamics during powered phases outside pendulum model applicability).

The main objectives are:

1. Develop a modular C++ software architecture:
 - Pendulum and mass-spring models,
 - CFD models (based on the CFD codes used for the construction of the dataset),
 - Integration of PINN/PIML models,
 - Interoperability with ECSS/SMP standards.
2. Explore, compare, and synthesize sloshing modeling methods:
 - Analytical approach (small angles, linear, pendulum),
 - Numerical CFD simulation (compressible gas and liquid with free surface, evaporation and thermal transport, extraction of wall forces),
 - Physics-Informed Neural Network (PINN), Neural Operator (NO) and Physics-Informed Neural Operator (PINO).
3. Propose a model selection strategy based on:
 - Required fidelity level,
 - Simulation constraints,
 - Flight phase and environment.

Methodological Approach

The thesis will rely on a structured approach divided into three main components:

1. Physical and numerical modeling of the fluid mechanics problem, with the aim of defining test cases (constant accelerations, transients, micro-gravity) and implementing them to, on one hand, characterize analytical models (pendulum and/or

mass-spring), and on the other hand, generate the datasets for neural network models.

An incremental approach may be envisioned in order to gradually refine the model with a growing complexity of phenomena to implement:

- incompressible gas-liquid system with a free surface,
 - gas compressibility and source terms,
 - thermal transport and phase change.
2. Development of full (CFD), reduced (pendulum), surrogate (PINN or PIML), and hybrid models according to ECSS/SMP standards for integration into an industrial environment that ensures good portability across various simulation environments.
 3. Performance evaluation on the trade-off between accuracy and speed through integration of models into a closed-loop digital simulator and development of recommendations for model selection based on usage.

Proposed Approach

Period	Step
Semester 1	Literature review, construction of test cases, mathematical formulation of the problem
Semester 2	CFD simulations, data extraction, initial PINN prototypes
Semester 3	Development of the modular library, integration of PINN and pendulum models
Semester 4	Evaluation, benchmarks, model selection strategy
Semester 5	Integration into simulators
Semester 6	Finalization, defense, software submission if applicable

Table 1: Project timeline

Scientific and Industrial Contributions

Accurate and fast evaluation tools for the modeling of propellants in launch vehicle tanks are expected.

In addition, this synthetic approach is expected to provide deeper insights into the limitations and complementarities of analytical models, CFD, and Machine Learning.

Specifically, a direct contribution is expected regarding the modeling of the physical phenomenon:

- A reduced model for sloshing in micro-gravity: where the state of the art does not provide anything usable in an environment coupled with GNC algorithms, unlike phases under acceleration.
- Initialization of pendulum models after an orbital phase: where the current state of knowledge forces us to randomly generate the initial state. The goal is to reduce such conservatism.

- Implementation of models during the flip maneuver of reusable launchers: where the dynamics of the launcher may impact sloshing behavior, moving beyond the applicability domain of pendulum models.

A direct contribution to the development of a launcher project, with the ability to simulate complete cases typically simulated via CFD coupling later in the project.

Finally, through integration into an industrial environment, we expect significant operational gains.

Indicative Bibliography

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Envisioned Collaborations

ESA, CNES, INRIA, ONERA

Host Laboratory

TBD

Acronyms

CFD Computational Fluid Dynamics. 1–4

CNES Centre National d’Études Spatiales. 5

ECSS European Cooperation for Space Standardization. 1–3

ESA European Space Agency. 5

FFNN Feedforward Neural Network. 1

GNC Guidance, Navigation and Control. 1, 3

INRIA Institut National de Recherche en Informatique et en Automatique. 5

ML Machine Learning. 3

NO Neural Operator. 2

ONERA Office National d’Études et de Recherches Aérospatiales. 5

PDE Partial Differential Equation. 1

PIML Physics-Informed Machine Learning. 1–3

PINN Physics-Informed Neural Network. 1–3

PINO Physics-Informed Neural Operator. 2

SMP Simulation Model Portability. 1–3