PhD in Modeling and Control of Space Systems
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PhD: Modelling and Control of Sloshing Phenomena for new Generation Space Missions

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Context & Motivation

Sloshing is the movement of a liquid in a partially filled reservoir. Modelling and controlling this phenomenon is paramount for the stability and performance of Space systems embarking liquid propellants. Sloshing was identified as the principal cause of the inefficient momentum damping observed during the anomaly of the Near Earth Asteroid Rendezvous (NEAR) mission and suspected to be the cause of the upper stage's instability that brought to the loss of the Falcon 1 mission in 2007. Moreover, the new tendency in Space exploration to bring man back to the Moon and beyond comes with the need for larger liquid propellant tanks to face longer missions. This poses new challenges in terms of safety and manoeuvre control performance.

Nowadays, only Computational Fluid Dynamics (CFD) models allow capturing sloshing phenomena in micro-gravity conditions, where surface tension forces become predominant over gravity and shape the fluid surface differently than on Earth. However, this numerical approach is computationally too expensive to be exploitable for model-based feedback control synthesis with a guaranteed certificate of stability and performance. Moreover, sloshing could also interact with the natural oscillatory modes of flexible appendages (i.e. solar panels, robotic arms, antennas) and get dramatically amplified.

The objective of this PhD is multidisciplinary and aims to finally join the paths of very different research areas (fluid dynamics, multi-body modelling and automatic control). The final goal is to provide a general framework to correctly simulate in real-time the coupling effects of sloshing phenomena in micro-gravity with vibrations effects of complex flexible Space structures under feedback control. Many are the applications in which this research question is still open: fine-pointing missions, rendezvous and docking (for refuelling), active debris removal and launcher coasting phase.

Research Questions

An experiment in microgravity (FLUIDICS) allowed the Institut de Mécanique des Fluides de Toulouse (IMFT) to validate CFD numerical simulations for a spherical tank rotating around one single axis for different filling ratios, acceleration and speed profiles [1]. This result is nowadays one of the most important in the literature on the experimental validation of sloshing in microgravity conditions. However, many fundamental questions remain open:

- Recent advances in scientific machine learning applied to fluid mechanics opened the doors to reduced-order models that can replicate CFD simulations. However, very few contributions are available for modelling sloshing phenomena in micro-gravity conditions. Can surrogate models obtained from CFD simulations be used to predict sloshing phenomena in microgravity experiments? Recent works of the authors at ISAE SUPAERO [2, 3] have proposed a methodology to train deep learning networks on high fidelity numerical simulations data in the field of liquid rocket engines combustion chamber design. Could this approach be extended to the sloshing problem?

- While a certain maturity has been reached in the control of very flexible spacecraft [4, 5, 6], sloshing phenomena still represent an unresolved obstacle in multi-body modelling area due to their highly non-linear behaviour. When dealing with real spacecraft applications, where flexible structures (like large solar panels, robotic arms, antennas, etc.) are involved, and the system is controlled in a closed loop, exchanges between fluid sloshing and the rest of the structures play an essential role in the mission stability and performance. These coupling effects can induce an undesired amplification of the natural modes of the system. Can the proposed framework deal with these coupling effects by integrating surrogate sloshing models into a multi-physics/multi-body simulation environment?

- Simple models for control synthesis have been extensively proposed in literature [7, 8]. However, these are restricted to simple scenarios and do not provide a generic framework to capture the real physics. Can an innovative control strategy be proposed based on the surrogate sloshing model and adaptable to different filling ratios? More specifically, it is of interest to combine approaches based on machine learning techniques [9, 10] with data assimilation [11, 12] and model-based control methods [13]. These are currently under development at the VKI for the modelling and controlling sloshing on-ground applications.

  The first has the advantage of deriving control strategies without relying on a model of the system dynamics but has the limitation of requiring a large number of interactions with the environment and does not leverage a large amount of prior knowledge of the system dynamics. The second has the advantage of being extremely efficient but must rely on a model of the dynamics that can, in some cases, be over-simplified: the combination of assimilation and reinforcement learning strategies could allow for training in parallel both the classic control agent in the reinforcement learning formalism and the surrogate model of the system dynamic (based for example on ANNs, as in [14, 15] or two-stage regressors, as in [16]), from which optimal control law could be derived analytically.

- Can the proposed framework, from modelling to closed-loop validation, be extended to other kinds of manoeuvres, such as linear translations (typical for rendezvous and docking scenarios), combined translations/rotations (as in the case of robotic arms), and attitude manoeuvres (for fine pointing missions) to answer to the open research questions on the use of liquid propellant for the next generation Space missions?

Short Research Plan

1. A bibliographical study will be performed to clearly identify the most promising approaches to model sloshing phenomena for control design purpose

2. Starting from the open-loop FLUIDICS benchmark, numerically validated by DIVA code, developed by IMFT, a reduced order model will be obtained for control synthesis purposes and closed-loop validation

3. The FLUIDICS benchmark will be extended to a closed-loop scenario in order to produce a high-fidelity simulator

4. Sloshing phenomena will be integrated into a flexible structure dynamics benchmark in order to capture the critical resonances between fluid and structure dynamics experienced in large flexible spacecraft

5. Robust control synthesis will be proposed in order to face sloshing control, and closed-loop validation on the high-fidelity simulator will be performed

6. An extension to linear translation, combined translation/rotation and attitude dynamics will be proposed in the same end-to-end framework presented in the previous steps (from modelling to validation) by going beyond FLUIDICS' pure rotational dynamics

7. An experimental validation of sloshing closed-loop control will be driven in von Karman Institute laboratory. This experiment, for which a modelling in 1g condition will be compulsory, will demonstrate the interest of the proposed approach by producing as outcome an available digital twin for control synthesis and validation.

Background

Modelling and control of complex Space systems have been at the heart of ISAE-SUPAERO's activities for a very long time. ISAE's expertise in space propulsion and transportation systems will also add value to the study. Many research topics related with the numerical simulation of reactive and two-phase flows in liquid rocket engines have been consolidated in recent years: supercritical combustion, thermoacoustic instabilities, nucleate boiling in micro-gravity, two-phase compressible flows, transcritical fluids, and heat transfer deterioration. The group has also developed a large experience in surrogate models from CFD and artificial intelligence. Moreover, ISAE SUPAERO signed in 2022 to create the ESA lab, Responsible and Sustainable Space Exploration.

The von Karman Institute for fluid dynamics has large expertise in the experimental characterization and the modeling of propellant sloshing. Moreover, in the last year, the group is leading the recent advances in machine learning for fluid dynamics for applications, including assimilation, closure modeling and control. These have been successfully applied in aeroacoustics' noise prediction, turbulence modelling, reduced-order modelling and time series forecasting, meshless integration of (partial) differential equations, super-resolution and flow control.

ISAE-SUPAERO and the von Karman Institute are also part of the ESA Topical Team on "Propellant Management Physics" with the scope of identifying the critical physical phenomena affecting the propellant behavior in tanks and define how to approach them in order to support a step forward in the state-of-art knowledge on propellant management. One of the outcomes of this activity is the contribution to the ESA SciSpacE White Papers (`https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Research/The_SciSpacE_White_Papers`) in the Applied Space Sciences - Propellant Management section.

Institut de Mécanique des Fluides de Toulouse (IMFT) provided in recent years the State-of-the-Art in predicting sloshing phenomena by Direct Numerical Simulations for two-phase flows. The approach validated by experiments in the International Space Station (ISS) is promising for studying the Physics of the next generation of Space missions.

Candidate Profile

You have a strong background in fluid dynamics, dynamics, control theory, linear algebra, and aerospace systems, demonstrated through an excellent undergraduate and/or master's degree performance. You are proficient in English, with excellent written and verbal communication skills. Prior research experience, such as participation in research projects, internships, or independent research work, is highly valuable.

Fundings

This PhD is a co-funded project (ESA, ISAE-SUPAERO, VKI) in the frame an OSIP initiative (`https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/The_Open_Space_Innovation_Platform_OSIP`).

Conditions of employment

Full-time employment for three years, including:

- A gross monthly salary and benefits in accordance to the ISAE-SUPAERO standard
- Receiving institutions: ISAE-SUPAERO (Toulouse, France), vonKarman Institute, ESA-ESTEC

Candidates are expected to start between the end of 2023 and the beginning of 2024.

Application

All applications should be compressed (.zip, 5MB max.) and submitted by email to the addresses below, including:

- Cover letter including a statement of purpose and previous experiences
- Detailed curriculum vitae
- Course grades transcripts
- Two recommendation letters

For more information regarding this position, please contact:

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