Aerospace Europe Conference 2023
Joint 10th EUCASS – 9th CEAS Conference

Abstract #XXX *(to be filled by the organizers)*
Preferred Topics: FDGNCAV / REUSYS / SYSINT

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Type: Oral
Status of corresponding author: Regular

Title

Modelling and Stability Analysis of Sloshing on Liquid-Propelled Reusable Launch Vehicles

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Abstract

The analysis of sloshing in liquid-propelled Launch Vehicles (LVs) and Reusable LVs (RLVs) is a critical aspect of their design and operation. This is because a significant percentage of the vehicle's take-off weight is composed of the liquids' masses contained within the oxidizer and fuel tanks. In the specific case of RLVs, a considerable amount of propellant is also necessary to perform the landing retro-propulsive burn. Furthermore, as the vehicle moves through the atmosphere, the trajectory profile and disturbances generate movement on the liquids, which produce forces that are transmitted back to the vehicle via the tanks' walls. When this phenomenon is not correctly understood and addressed accordingly, it can intensify critical instabilities in the control system, and thus lead to total vehicle loss.

During ascent and descent flight, the fluids within an RLV experience a high-gravity regime, this means the fluid dynamics is better explained through the Bond number. Under these assumptions, well-understood analog mechanical models can be employed for different tank geometries. Two of the commonly used models for simulation and control design include the spring-mass and spherical pendulum. In this article, we exploit the pendulum model for cylindrical tanks with spherical domes, which covers a substantial part of the current architectures used in LVs and RLVs. For the estimation of the mechanical parameters, we employ mathematical models that have been refined over the past decades; they are good approximations that are valid for GNC design [1]. In our investigations, we perform the analysis for a real 44 KN-class vehicle, an RLV with a gimbaling engine, flying a typical Return to Launch Site (RTLS) scenario trajectory [2][3]. The results are then compared to Computer Fluid Dynamics (CFD) simulations for the same trajectory profile with varying-mass fluids.

In the second part, we focus on the modeling of the 6-DoF coupled equations of motion for a generalized rigid-body system with n-pendula attached at different points along its structure. With this purpose, the iterative Newton-Euler method for multibody systems [4] is employed. This analytical model provides a good general representation in vector form, which can be easily implemented in a simulation environment. The reasoning behind the reduction of the earlier set of equations, to a planar flight representation first, and later to a linear state-space model that can be used for control design and stability analysis; is thoroughly described. These contributions are of great interest to the community.

In the final part, we analyze the stability of the CALLISTO vehicle upon the position of the sloshing masses with regards to the so-called “danger zone” [5][6], which is the region situated between the center of mass and the center of percussion. When any of the masses cross this region, the control system might indirectly inject energy into the mode, which together with an unfavorable phasing, is the perfect formula for instability. This type of analysis commonly leads to the introduction of baffles to passively stabilize the modes, but this must be done early in the design phase to avoid mass penalizations from the introduction of extra devices at later stages. Finally, the closed-loop behavior of the studied vehicle is analyzed together with a structured H_∞ rigid body controller for the ascent phase from our earlier investigations [3][7]. There exist extra challenges associated with a correct frequency separation between the lower-frequency modes and the rigid body closed-loop bandwidth. Due to the proximity of both frequencies, a control design including direct anti-resonance filtering is not possible. Furthermore, all previous propositions are also validated via 6-DoF simulations.

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