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DESIGN OF FLIGHT CONTROL SYSTEMS FOR RLVS WITH STRUCTURAL FLEXIBILITY: APPLICATION TO THE CALLISTO VEHICLE

Abstract

The analysis of structural flexibility in Launch Vehicles (LVs) and Reusable LVs (RLV) is a critical aspect during the design and operation of the Guidance, Navigation and Control (GNC) subsystem. This characteristic becomes even more critical as vehicles are becoming larger and slender due to conflicting objectives: 1) needing to deploy larger payloads into orbit and, at the same time, 2) reducing losses due shape-induced drag. During its flight across the atmosphere, several forces acting interact with the vehicle's structure i.e., those produced by the actuators (Thrust Vector Control (TVC), Reaction Control System (RCS) and/or fins) or disturbances like the aerodynamic forces produced by the body itself.

Addressing this problem from a GNC perspective requires understanding of structural mechanics. The usage of mechanical equivalent models that capture the core dynamics is necessary, the parameters are conventionally extracted from more accurate, but computationally expensive, methods like Finite Element Method (FEM) analysis. The high frequency response is typically decomposed as the sum of the harmonic response of n modes. Each mode is characterized by a natural frequency ω_{ni} and a modal shape Φ_j, which changes depending on the viewpoint (force application location or measurement location). The initial and natural step is to look at the positioning of the frequencies relative to the desired rigid-body bandwidth. Moreover, on the frequency domain, bending modes are translated into resonances with gain amplification and phase shift, which in terms of the control systems means; correct gain and phase margins in the closed-loop are required.

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 and variable mass. Firstly, we present the evolution of the frequencies and modal shapes across the trajectory for the ascent phase. Secondly, we present problem formulation from a control perspective, the n modes are introduced into the state-state representation from our previous investigations, and subsequently employed for control synthesis. Thirdly, the modes are stabilized using anti-resonance filters to guarantee adequate high-frequency stability margins.

In the final part, the closed-loop behavior of the flight control system for the CALLISTO vehicle is analyzed under the influence of structural flexibility. The performance of an H_∞ synthesized rigid body controller from our earlier investigations is consequently validated. Monte-Carlo simulations are run on the software-in-the-loop simulator for this mission under nominal and uncertain conditions.