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Advanced Anti-Sloshing Strategies for Cryogenic Tanks: A Two-Way Fluid-Structure Interaction Approach

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Sloshing in aerospace cryogenic tanks generates dynamic loads that can significantly impact vehicle stability and control, with effects strongly dependent on the fluid-filling ratio. Traditional anti-sloshing strategies, such as fixed baffles, often fail to provide uniform damping across varying liquid volumes. This study is aimed at developing a design methodology for more effective anti-sloshing systems, highlighting promising solutions such as floating decks, flexible baffles, and other innovative configurations. Due to the small density difference between the anti-sloshing device material and the cryogenic propellant, strong fluid-structure coupling effects arise, necessitating a two-way Fluid-Structure Interaction (FSI) simulation to accurately capture the mutual influence between the fluid motion and the structural response.

A partitioned two-way FSI approach is employed, coupling Computational Fluid Dynamics (CFD) in ANSYS Fluent with a Finite Element (FE) solver that captures the structural response of the anti-sloshing system. The Volume of Fluid (VOF) method is used to capture free-surface dynamics. Key design parameters, including material stiffness, mass distribution, and geometric configurations, are taken into account as part of the proposed analysis methodology. Among the innovative solutions, floating decks and flexible baffles appear particularly promising for achieving a higher and more uniform damping profile.

Replication of a benchmark from literature is performed to assess whether the numerical simulation approach for such complex, strongly coupled systems is feasible in terms of both response accuracy and computational cost.

This comparison provides valuable insights into the complex interplay between fluid motion, device flexibility, and internal damping mechanisms. The proposed methodology enhances predictive capabilities for aerospace cryogenic tank design, ultimately supporting the development of more robust and efficient fuel management systems, an essential step to mitigate sloshing-induced instabilities in launch vehicles, satellites, and in-space propulsion systems, thereby contributing to safer and more efficient space missions.

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