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PROCEEDINGS

Velocity-Dependent Aerodynamic Control Effectiveness of a Single-Segment Flapping-Wing Vehicle

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ABSTRACT

Robust flight control is the key for the success of single-segment flapping-wing vehicles. This study introduces an analytical framework utilizing a velocity-dependent aerodynamic control effectiveness matrix, which take the aerodynamic constrains into consideration. By linearizing the nonlinear six-degree-of-freedom (6-DOF) rigid-body model at representative trim conditions to construct a linear parameter-varying (LPV) representation, state-space control matrices are efficiently extracted across the continuous flight envelope. The investigated platform, Aquila-S, utilizes flapping frequency as the primary active force for thrust and an all-moving horizontal tail to manage attitude. System identification via rigorous wind tunnel testing is conducted to precisely extract aerodynamic derivatives and validate the theoretical structure of the control matrices. Furthermore, quantitative evaluation utilizing controllability metrics and specialized decoupling indices reveals that achievable flight performance is fundamentally constrained by the distribution of aerodynamic control authority. Wind tunnel validations confirm that at low speeds, tail surfaces exhibit very poor control efficiency, forcing an over-reliance on flapping frequency that inextricably couples speed and altitude dynamics. At medium speeds, the control matrix achieves an optimal balance, naturally facilitating effective dynamic decoupling. In contrast, at high speeds, excessive aerodynamic sensitivities mandate a strict reduction in tail control coefficients. Simulations of representative mission tasks, including level flight, continuous climb, and turning maneuvers, demonstrate the inherent limitations of fixed-gain controllers. These findings bridge aerodynamic mechanisms with flight control design, and suggest that adaptive gain scheduling techniques are necessary to ensure robust stability across the entire speed envelope.

KEYWORDS

Flapping-wing vehicle; aerodynamic control effectiveness; linearization parameter variation; controllability; gain scheduling

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