AEROELASTICITY STUDY OF MULTI-BODY COMBINED UNMANNED AERIAL VEHICLES

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ABSTRACT

Multi-body combined unmanned aerial vehicles (UAVs), formed by mechanically connecting multiple single UAV units, have emerged as a promising configuration for achieving high aerodynamic efficiency while alleviating the structural penalties associated with large-aspect-ratio wings. By employing wing-tip hinged connections, such configurations can significantly reduce wing root bending moments, suppress severe geometric nonlinearities, and maintain the operational flexibility of individual flight units. However, the introduction of inter-vehicle constraints fundamentally alters the flight dynamics of the system. In particular, wing-tip-connected multi-body combined UAVs exhibit inherent coupled motion modes that may lead to dynamic instability, making active stabilization indispensable for safe flight.

Most existing studies on multi-body combined UAVs rely on rigid-body flight dynamics models, in which structural flexibility and aeroelastic effects are neglected.

Since 2019, An et al. have investigated the dynamics of multi-body combined UAVs using the Newton–Euler formulation and lifting-line theory, revealing the existence of relative roll instability modes that prevent stable flight without stabilization control. Subsequent three-UAV combination flight tests demonstrated relatively smooth combined flight, although stable landing of the combined system was not achieved.[1]

In 2021, Wu et al. studied the effects of wingtip connections on reducing energy consumption and extending endurance of solar-powered aircraft, deriving models for the Oswald efficiency factor, induced drag coefficient, and power consumption. [2]

German researchers have studied wingtip-connection technology. In 2017, Kothe et al. at the Technical University of Berlin developed a control system for wingtip-connected UAV assemblies and built a three-UAV wingtip-connected technology demonstrator.[3][4]

This simplification limits the applicability of such models, especially for high-aspect-ratio configurations where elastic deformation, aerodynamic loading redistribution, and control interactions are strongly coupled. To address these limitations, this study investigates the aeroelastic response and stability augmentation control of a wing-tip-hinged two-body composite UAV by explicitly accounting for structural flexibility and unsteady aerodynamics.

The structural dynamics of the composite UAV are formulated using the floating frame of reference method combined with modal coordinates. This approach enables the

decomposition of motion into large rigid-body displacements and small elastic deformations, allowing efficient modeling of flexible multi-body systems. The wing-tip hinge is modeled as a single-degree-of-freedom rotational constraint, permitting relative roll motion between adjacent UAV units while constraining all other relative motions. Constraint equations are incorporated into the system dynamics through the Lagrange multiplier method, yielding a unified set of flexible multi-body equations of motion.

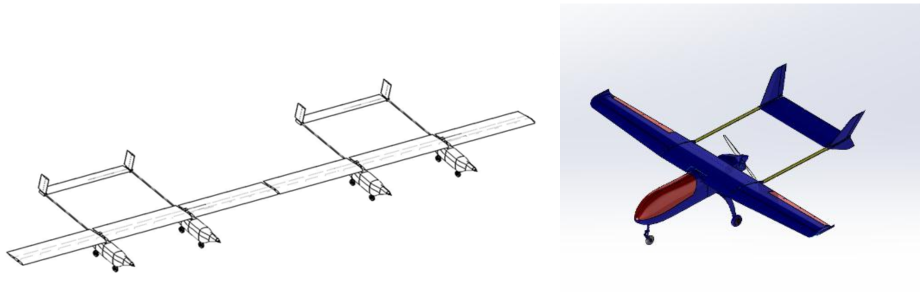


Fig.1: Aircraft schematic and axonometric views

Aerodynamic forces are computed using strip theory, which reduces the three-dimensional wing aerodynamics to a series of two-dimensional sectional problems along the span. For each aerodynamic strip, unsteady aerodynamic loads are evaluated using induced theory, which represents induced velocity effects through a finite set of state variables. Spanwise aerodynamic corrections are introduced to account for the unique boundary conditions of the wing-tip-connected configuration, in which edge effects occur only at the outermost wing tips of the composite system.

An integrated time-domain aeroelastic simulation framework is established by coupling a flexible multi-body structural model developed in ADAMS with an aerodynamic and control model implemented in MATLAB/Simulink. Based on this framework, trim conditions of the composite UAV are solved, and linearized stability analyses are performed. The results reveal the presence of additional coupled motion modes that do not exist in conventional single-body aircraft. One of these modes is identified as a divergent relative roll mode, indicating that the composite UAV is dynamically unstable in the absence of active control.

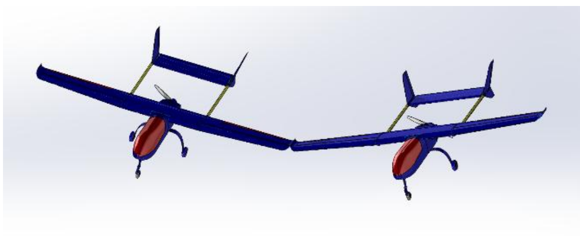
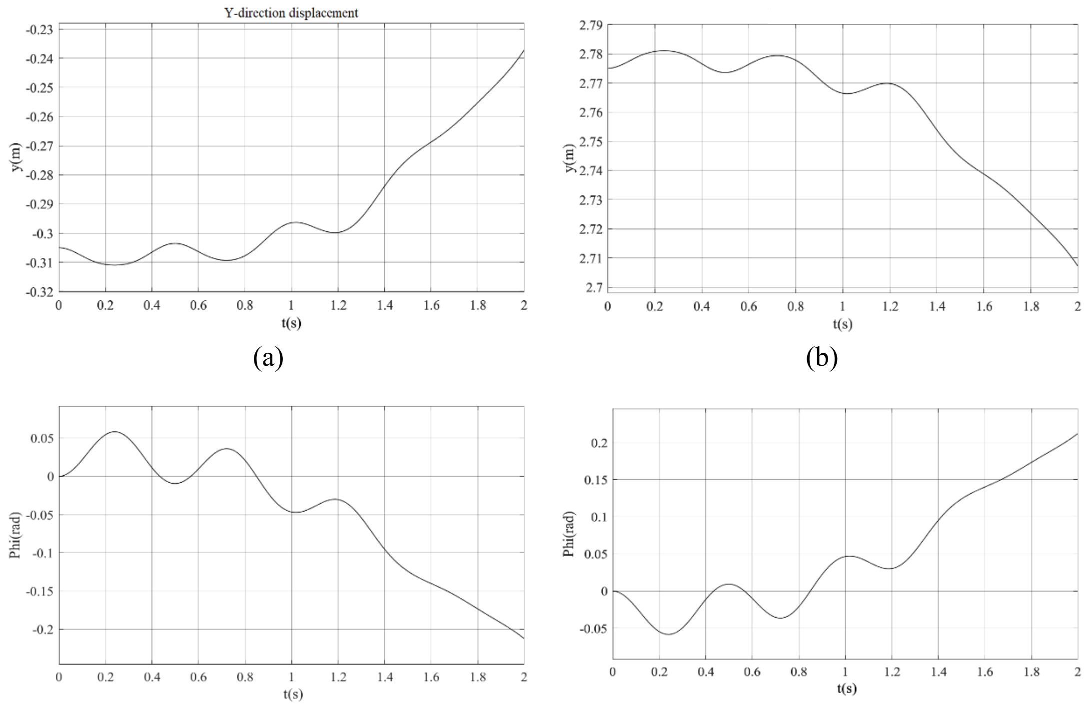


Fig2: Schematic of composite mode

To suppress this instability, a roll stability augmentation controller based on PID control is designed, using relative roll angle feedback and aileron deflection as the control input. Controller parameters are tuned using time-domain simulations. Nonlinear aeroelastic simulations demonstrate that the proposed control strategy effectively stabilizes the divergent mode and enables steady, coordinated flight of the flexible multi-body composite UAV.



(a) (b)

(c) (d)

Fig3:Y-direction displacement and roll-angle response curves of the two aircraft.

This study provides a comprehensive aeroelastic modeling and control framework for multi-body composite UAVs and offers theoretical and numerical support for their future design and application.

Keyword: Multi-body combined UAV, Aeroelasticity, Flexible multibody dynamics, Stability augmentation, Wing-tip connection

Reference:

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