

A COMPUTATIONAL FRAMEWORK FOR ANALYZING FOLDING WING TIP DYNAMICS ON HIGHLY FLEXIBLE WINGS: A FLEXIBLE MULTIBODY FORMULATION

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ABSTRACT

The aviation industry's pursuit of enhanced aerodynamic efficiency has led to a significant trend towards aircraft designs featuring substantially larger wingspans. This technological advancement, however, introduces considerable infrastructure and operational challenges at airports worldwide. To address these constraints, innovative technologies such as Folding Wing Tips (FWT) have emerged as a viable solution, enabling aircraft to maintain extended wingspans for improved aerodynamic performance during flight while allowing for retraction during ground operations. Since the implementation of FWTs inevitably adds structural complexity and additional weight to the aircraft, their design necessitates functional in-flight benefits to economically offset these penalties. The most critical advantage sought is the ability to perform effective gust load alleviation, reducing structural loads and enabling lighter, more fuel-efficient aircraft designs.

Current scientific literature reveals a significant gap: there is a lack of comprehensive computational models that effectively capture the fully coupled nonlinear dynamics of highly flexible aircraft integrated with FWTs. This modeling complexity arises from the simultaneous occurrence of three interacting phenomena: large rigid-body motions of the aircraft, high elastic deformations of the wing structure, and highly nonlinear aerodynamic forces. Traditional approaches that assume small deflections or linear aerodynamic effects are fundamentally inadequate for the accurate prediction of FWT behavior in this coupled environment. The primary objective of this research is the development and rigorous validation of a robust computational framework specifically tailored for the aeroelastic analysis of these complex systems, bridging the gap identified in prior research [1].

The core contribution of this work is the development of the Highly-flexible Multibody Aeroelastic Simulation Tool (HMAST). The methodology is constructed upon a substructuring philosophy intentionally designed to bridge the gap between local structural linearity and global geometric nonlinearity. The structural domain is modeled using a flexible multibody dynamics approach based on the floating frame of reference formulation, which naturally decouples rigid-body motion from elastic deformations [2].

Each body within the multibody system is described using the Rayleigh-Ritz method, where elastic displacements are approximated by a carefully selected set of admissible shape functions. This approach allows for a significant reduction in the number of degrees of freedom while maintaining fidelity in capturing local structural deformations. Importantly, the global nonlinearity of the structure is not modeled within the bodies themselves but emerges naturally from the kinematic constraints and large excursions between the interconnected reference frames. To ensure numerical stability during the integration of the resulting Differential-Algebraic Equations (DAEs), the framework employs index reduction techniques coupled with the Post-Stabilization (PStab) method. This effectively mitigates the numerical drift

phenomenon often observed in constrained multibody dynamics, ensuring that the velocity and position constraints are strictly satisfied throughout the simulation [3].

The aerodynamic environment is simulated using a non-planar Vortex Lattice Method (VLM). This represents a crucial distinction from classical planar aeroelastic codes; in HMAST, the aerodynamic mesh is dynamically updated at every time step to conform to the instantaneous deformed shape of the multibody system. This dynamic mesh updating enables the correct calculation of aerodynamic loads as follower forces, which is essential when the wing tip undergoes significant folding or when the main wing experiences large displacements.

The HMAST framework underwent a rigorous multi-stage validation process to ensure reliability. Initial benchmarks focused on purely structural cases, comparing the Rayleigh-Ritz multibody approach against analytical solutions for cantilever beams and results from commercial software. These tests confirmed the framework's ability to accurately predict large deflections and natural frequencies of highly flexible members. Subsequently, the aeroelastic coupling was validated using classic flexible wing benchmarks from established literature.

Following successful validation, the tool was applied to analyze a very flexible wing equipped with a passive FWT system. The study focused on the dynamic response to realistic one-minus-cosine gusts of varying durations ($T = 0.3s, 0.5s, 0.7s$), representing a range of atmospheric disturbances typical of flight operations. The FWT was modeled with passive hinge stiffness, allowing for uncontrolled rotation without external actuation.

The results highlight the transformative potential of FWTs for structural weight reduction. Figure 1 presents the time-history of the Wing Root Bending Moment (WRBM), Wing Root Torsion Moment (WRTM), and the Folding Angle (FA) during gust encounter. The analysis reveals that as the gust hits the wing, the FWT begins to fold upward. This motion effectively reduces the local angle of attack at the tip and shifts the center of pressure inboard, significantly decreasing the lever arm of the lift force. For the most critical gust duration (0.7s), the HMAST simulation predicted a reduction of 24.33% in the peak WRBM variation. Even more striking is the impact on the WRTM, which saw a reduction of 90.36%. This occurs because the folding motion not only reduces lift but also reorients the lift vector, drastically changing the twisting moment applied to the wing box.

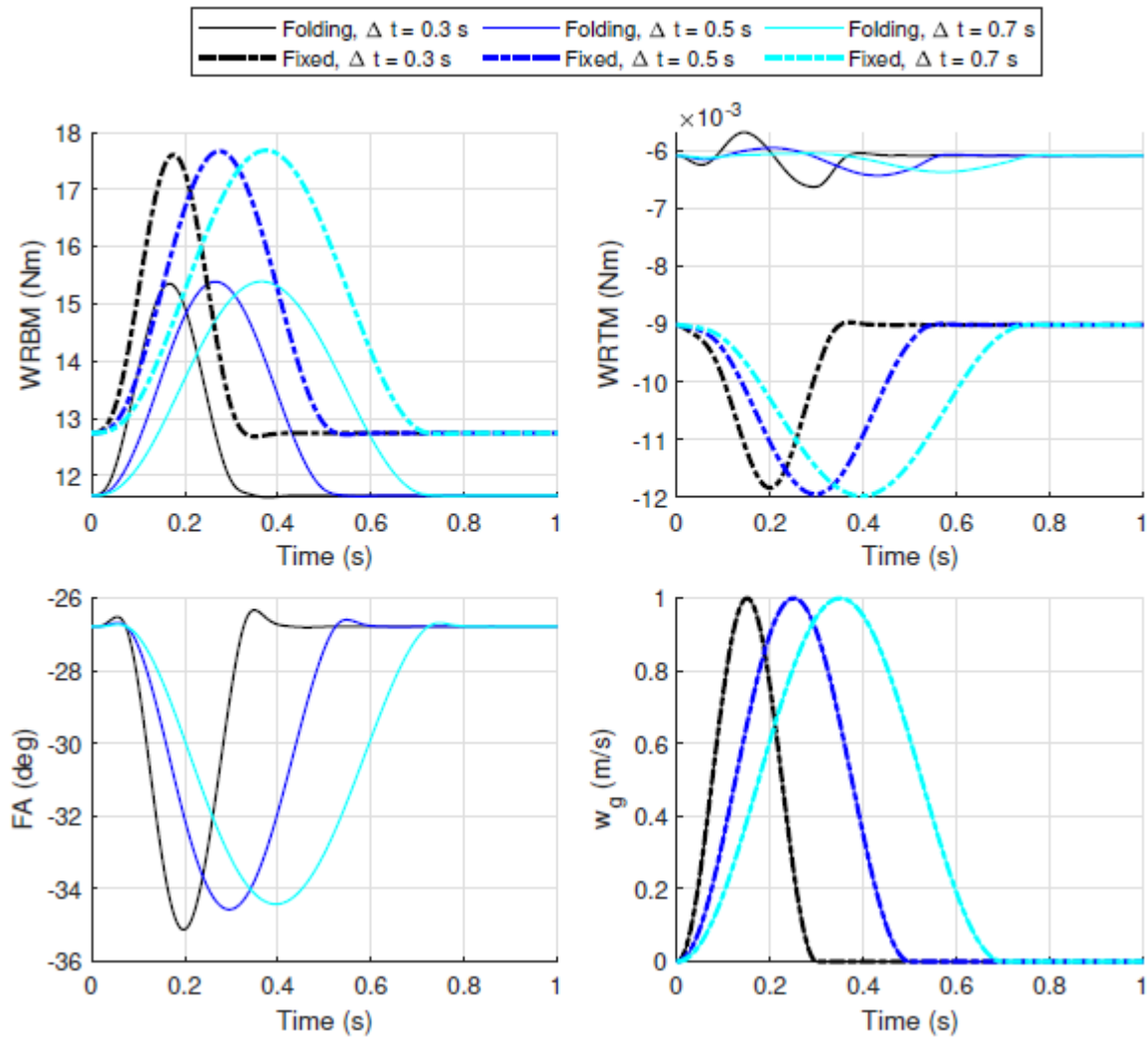


Figure 1. Temporal comparison of WRBM, WRTM, and FA for different gust durations.

This research successfully demonstrates that the HMAST framework is a robust and computationally efficient tool for the analysis of next-generation highly flexible aircraft equipped with FWT systems. By capturing the essential nonlinearities of highly flexible wings through an integrated multibody Rayleigh-Ritz approach and non-planar VLM, the tool provides insights that linear methods fundamentally cannot capture. Future developments will involve the integration of active control laws for the folding mechanism, aiming to further optimize the flight envelope and achieve additional load alleviation beyond passive systems.

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