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PRELIMINARY STRUCTURAL DESIGN TOOL FOR FLEXIBLE SLENDER BODIES WITH AEROELASTIC CONSTRAINTS

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Modern slender-body flight vehicles are designed for improved performance, including longer range, better maneuverability, and higher payload capacity. These goals drive new designs toward long, lightweight configurations with higher lift-to-drag and thrust-to-weight ratios. As a result, current vehicles often have length-to-diameter ratios near 20:1 and payload-to-structure mass ratios above 15:1. In these designs, the load-bearing structure accounts for only a small fraction of the total mass, making them much more flexible than traditional designs. The reduced stiffness leads to increased elasticity and lower natural frequencies, which introduce significant aeroelastic effects that must be accounted for in the design.

For slender bodies, where lift is concentrated at the nose and rear fins, the body flexes, shifting the aerodynamic center forward, thus impacting lift, control effectiveness, and static stability. Although these effects have been known for decades [1], designers still lack practical tools for efficient aeroelastic evaluation during the conceptual design phase. Aeroelastic analysis methods typically rely on detailed structural and aerodynamic models that are too costly for early-stage parametric studies. As a result, slender-body aeroelasticity is often acknowledged but not assessed until later phases, when design changes are difficult and expensive.

This study presents a preliminary design tool that addresses this gap by proposing a computationally efficient and easy-to-implement approach to evaluate static aeroelastic deformations and their impact on the stability of flexible slender bodies. The methodology builds on analytical structural modeling utilizing the Assumed Modes approach [2], coupled with the aerodynamic load distributions of the assumed known rigid geometry. The latter can be computed using aerodynamic models of varying fidelity in commercially available codes. The structural and aerodynamic models form the basis of AIDTOOL, the Aeroelastic Initial Design Tool. AIDTOOL computes elastic deflections, aerodynamic load distributions over the deformed body, and assesses changes in the stability margin for selected flight conditions. A built-in sensitivity analysis provides rapid feedback on how design choices, such as shell thickness and mass distribution, influence aeroelastic behavior and stability trends. Figure 1 shows an example of a deformed slender body analyzed by AIDTOOL.

AIDTOOL was validated by comparing trim analysis results to those computed by the ZAERO aeroelastic software [3]. It produced similar trends in aeroelastic response, with stability-margin predictions differing by roughly ten to fifteen percent (on the conservative side), which is acceptable for preliminary design and can be managed with standard safety factors. AIDTOOL captures the main aeroelastic effects with reasonable accuracy while remaining computationally efficient. A parametric study of 1,080 different structural configurations identified designs with 30% less structural mass that satisfy stability constraints. The study identified several useful

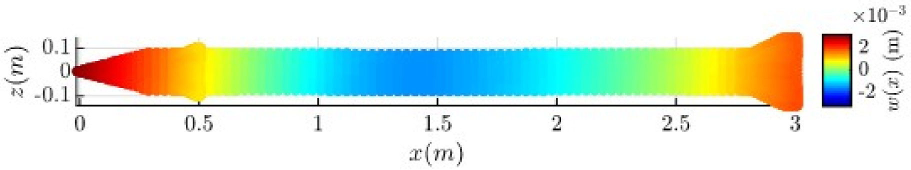

Figure 1: An example of elastic deformations of a slender body configuration as computed by AIDTOOL

design guidelines, such as increasing envelope thickness, shifting mass forward, and stiffening aft sections to reduce stability-margin loss. These trends demonstrate how the tool can guide structural design choices early in the design process.

To further demonstrate its usefulness, AIDTOOL was combined with a genetic-algorithm optimization scheme. The optimizer searched for structural layouts that satisfy aeroelastic constraints while reducing mass. The resulting optimal configuration meets stability requirements, demonstrating that the tool can support automated design exploration in addition to manual trade studies.

The full paper will provide a presentation of the AIDTOOL methodology and its application to flexible slender body design. It will include the mathematical derivation of the structural modeling approach, as well as the formulation for the aerodynamic load distribution for slender geometries. A complete test case of a multi-section slender vehicle will be presented, demonstrating the tool's application workflow from initial geometry definition through structural parameter variation to stability margin evaluation. The verification methodology comparing AIDTOOL predictions against established commercial aeroelastic software will be fully documented. Finally, the paper will present the parametric investigation and optimization integration results, illustrating how AIDTOOL can support both manual design exploration and automated optimization processes in the preliminary design phase.

1 References

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