DEVELOPMENT OF STRUCTURAL REDUCED ORDER MODEL FOR MODAL BASE AEROELASTIC SOLVERS VIA GLOBAL OPTIMIZATION

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ABSTRACT

Dynamic aeroelasticity analyses, such as flutter and gust response evaluations, are essential for aircraft certification and must be repeated for thousands of mass, center of gravity (CG), and payload configurations. While high-fidelity 3D Global Finite Element Models (GFEM) provide accuracy, their computational cost is often prohibitive for iterative design and multidisciplinary optimization. Existing literature often focuses on isolated components or limits analysis to primary bending and torsion modes, frequently neglecting the joint modeling of lifting and control surfaces. This study presents a methodology to generate a 1D Beam Stick Model (BSM) of a complete aircraft that retains the dynamic characteristics of a 3D GFEM with high fidelity while significantly reducing analysis time.

The methodology utilizes a Modified Crow Search Algorithm (CSA) [1], a swarm-intelligence meta-heuristic method, to optimize the cross-sectional properties of beam elements. To enhance the original algorithm, a multi-objective approach was implemented:

- **Multi-Objective Optimization:** Simultaneously minimizing natural frequency differences and maximizing Modal Assurance Criteria (MAC) values between GFEM and BSM.
- **Novel Control Surface Coupling:** A specialized methodology for connecting control surfaces to lifting surfaces.
- **Component-Wise Assembly:** The BSM is built by isolating and optimizing individual components (wing, fuselage, tails) before final assembly to ensure local and global fidelity.

The methodology was validated on the METU Very Light Aircraft (VLA). for which both the high-fidelity GFEM and the optimized BSM are illustrated in Figure 1.

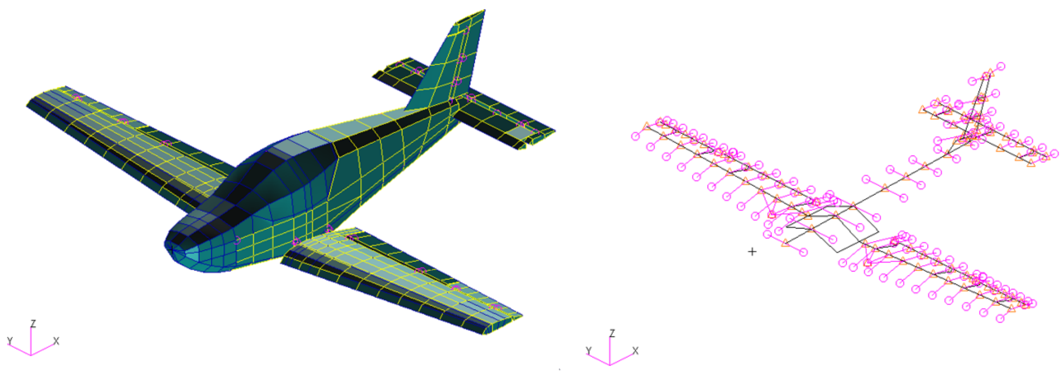

Figure 1: GFEM and BSM of METU VLA

The assembled BSM successfully captured the first 20 elastic modes of the GFEM with a maximum frequency difference of only 3.1%. MAC values for 18 out of the first 20 elastic modes exceeded 0.95, indicating excellent mode shape correlation. Modal correlation between the GFEM and BSM is quantified using the Modal Assurance Criterion (MAC), as shown in Figure 2.

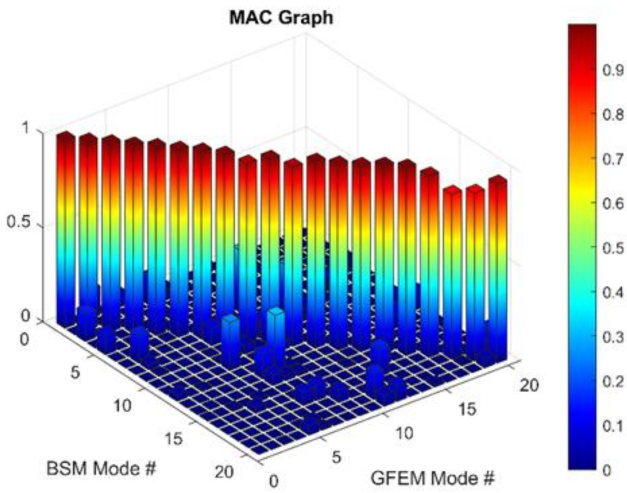

Figure 2: MAC graph between GFEM and BSM

Four distinct flutter mechanisms were identified. The BSM predicted flutter onset speeds within 4.5% and flutter frequencies within 3.3% of the high-fidelity GFEM results. Comparisons of flutter mechanisms and Vg-Vf characteristics obtained from the GFEM and BSM are presented in Figure 3.

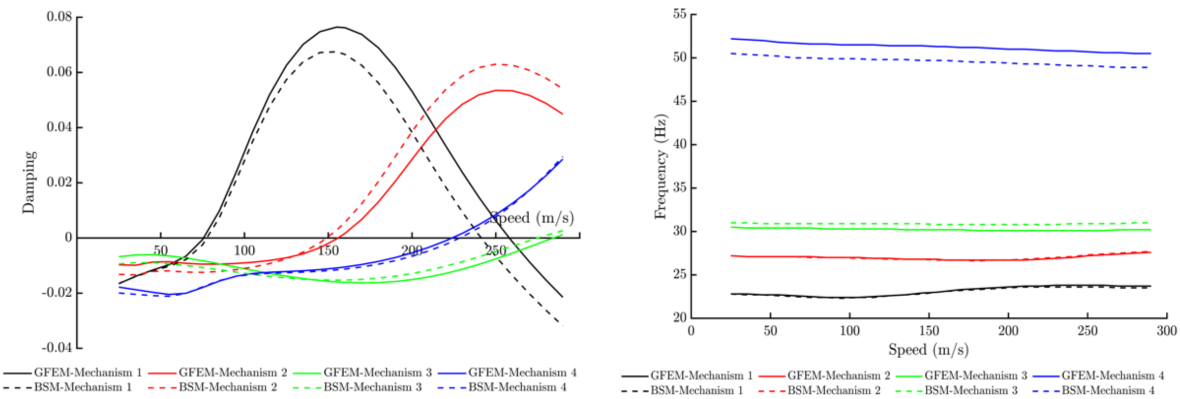

Figure 3: Comparison of Vg-Vf graphs

Comparisons of vertical acceleration at the CG and root bending moments under discrete gust loads showed nearly identical time-history responses between the two models as shown in Figure 4.

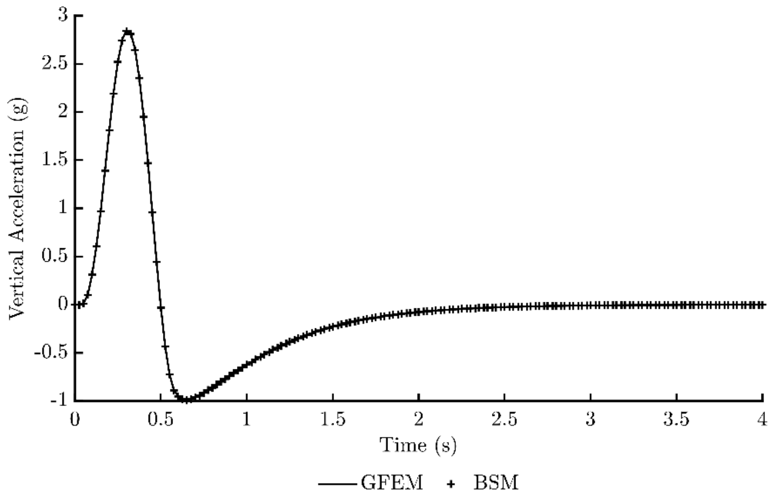

Figure 4: Comparison of the vertical acceleration at the CG vs time

In this study, a global-optimization-based methodology for generating high-fidelity beam stick models of complete aircraft configurations has been presented and validated. The proposed approach introduces a multi-objective optimization framework and a novel control-surface coupling strategy, enabling accurate representation of both global and local dynamic characteristics within a reduced-order model. Numerical results demonstrate that the optimized BSM accurately predicts modal properties, flutter characteristics, and gust responses of the reference GFEM, with errors remaining within engineering-acceptable limits. These findings indicate that the proposed methodology provides a robust and computationally efficient alternative for rapid aeroelastic assessment and design-space exploration in early and certification-driven aircraft development phases.

References

[1] A. Askarzadeh, “A novel metaheuristic method for solving constrained engineering optimization problems: Crow search algorithm,” *Comput Struct*, vol. 169, pp. 1–12, Jun. 2016, doi: 10.1016/j.compstruc.2016.03.001.