

COMPUTATIONAL ASSESSMENT OF AERODYNAMIC SHAPE OPTIMIZATION FOR AEROELASTIC SCALING: 2D AIRFOIL VS. 3D WING OPTIMIZATION

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Abstract

Modern aircraft design increasingly relies on high aspect ratio configurations to maximize efficiency, resulting in highly flexible structures that experience large geometric deformations and significant aeroelastic nonlinearities. Validating efforts for these phenomena heavily depend on sub-scale models. A suitable aeroelastic scaling must replicate both structural dynamics and unsteady aerodynamics. While dynamic similarity can be achieved by tuning internal mass and stiffness, attaining simultaneous aerodynamic similarity is severely hindered by fundamental flow mismatches at reduced scales.

Scaling down a flexible wing significantly drops its Reynolds number (Re). This reduction alters boundary layer thickness and pressure gradients. For highly flexible wings, whose structural shape depends entirely on aerodynamic loading, the mismatched aerodynamic influence corrupts the aeroelastic equilibrium state and the dynamic flutter boundaries. To bridge this gap, aerodynamic shape optimization is often employed to pre-distort the sub-scale model's outer shape, artificially recovering "full-scale equivalent" forces at low Re . However, a critical research gap persists. It remains unclear whether computationally inexpensive 2D sectional airfoil optimization is sufficient to recover true aeroelastic similitude, or, if costly fully 3D wing optimization is strictly required.

This study proposes a purely computational optimization framework to evaluate shape tailoring strategies for aeroelastic scaling. Using a highly flexible benchmark wing (e.g., the Pazy Wing), the internal structure is mathematically scaled for dynamic similarity while the external aerodynamic shape is then subjected to two distinct optimization routines:

Gradient-based optimization is applied at the 2D airfoil level to minimize the discrepancy between full-scale and sub-scale sectional pressure distributions at the target Re . The optimized profile is then lofted along the span.

A comprehensive aerostructural optimization where the entire 3D external geometry is optimized.

The study employs high-fidelity Computational Fluid Dynamics (CFD) coupled with a nonlinear structural solver. The geometrically scaled baseline, 2D optimized, and 3D optimized models will be subjected to identical virtual flow conditions. The analysis focuses on how accurately each method recovers the full-scale aeroelastic load distribution. Since 2D optimization inherently neglects spanwise crossflow and 3D induced drag scaling, the study quantifies the resulting error in the aeroelastic equilibrium. The primary objective is to precisely evaluate the trade-off between computational cost and aeroelastic accuracy.

This research provides critical guidelines for the aeroelasticity and optimization communities. By systematically comparing 2D and 3D shape optimization for this objective, it establishes a computational framework for designing sub-scale aeroelastic models. This will allow engineers to appropriately allocate computational resources without compromising the nonlinear physical phenomena required for accurate fluid-structure interaction validation.