GEOMETRIC PARAMETER-BASED SURROGATE MODELLING FOR AEROELASTIC ANALYSIS OF NOVEL AIRCRAFT CONFIGURATIONS

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ABSTRACT

The preliminary design phase of unconventional aircraft configurations such as blended wing body (BWB) aircraft presents significant computational challenges when accounting for interaction between aerodynamic loads and structural deformations. Conventional high fidelity aeroelastic analysis workflows rely on computationally expensive RANS-based CFD coupled with FEA, making comprehensive design space exploration prohibitively time-consuming during early-stage development. This work presents a methodology that develops geometric parameter-based aerodynamic surrogate models trained on high-fidelity CFD data to rapidly approximate aerodynamic forces for predicting static aeroelastic deformation of complex configurations including BWB.

The proposed methodology reduces the computational overhead of CFD while maintaining sufficient accuracy for preliminary design decisions. Equation 1 shows that the force acting on the surface at any given time and location is a function of the flow parameters, the geometry and the fluid properties. For static deformations we assume the flow is steady and the aircraft state is in equilibrium and the fluid properties are constant. Hence the forces acting at any point on the aircraft surface is function of the flow properties and the geometric parameters alone.

By encoding geometric variations through a subset of geometric parameters, the surrogate models enable rapid prediction of aerodynamic loads, eliminating iterative CFD computations during the aeroelastic analysis loop.

$$F_{aero}(x) = F(\theta_{flow}, \theta_{geometry}, \theta_{fluid}) \tag{1}$$

Where:

- x = spatial position
- θ_{flow} = freestream velocities in x,y,z directions (V_∞, α, β)
- $\theta_{geometry}$ = geometric shape parameters
- θ_{fluid} = fluid properties (ρ_∞ (freestream density), μ_∞ (dynamic viscosity), γ (ratio of specific heats))

The methodology is applied on two complementary databases [1][2]. The AIRFRANS database [1], comprising over one thousand high-fidelity RANS simulations of NACA airfoil series, provides detailed pressure distributions for developing robust surrogate models for sectional aerodynamic characteristics. The BlendedNet database from Harvard Dataverse [2], containing RANS simulations of 999 unique BWB geometries with detailed pointwise surface coefficients (Figure 1), is used for the 3D aerodynamic surrogate development. Figure 2 demonstrates the agreement between surrogate predictions and CFD computations for pressure distribution over a typical airfoil section, validating the approach for 2D cases. These databases enable construction of multi-fidelity surrogate models with computational efficiency orders of magnitude greater than traditional CFD.

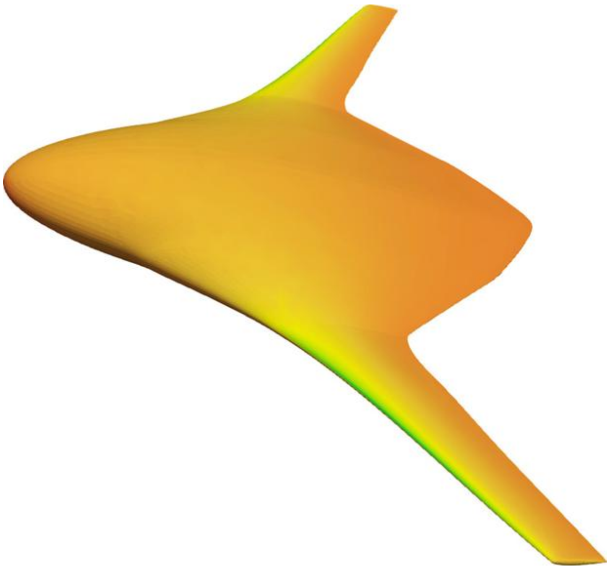

Figure 1: CFD pressure distribution on Blended Wing Body geometries [2]

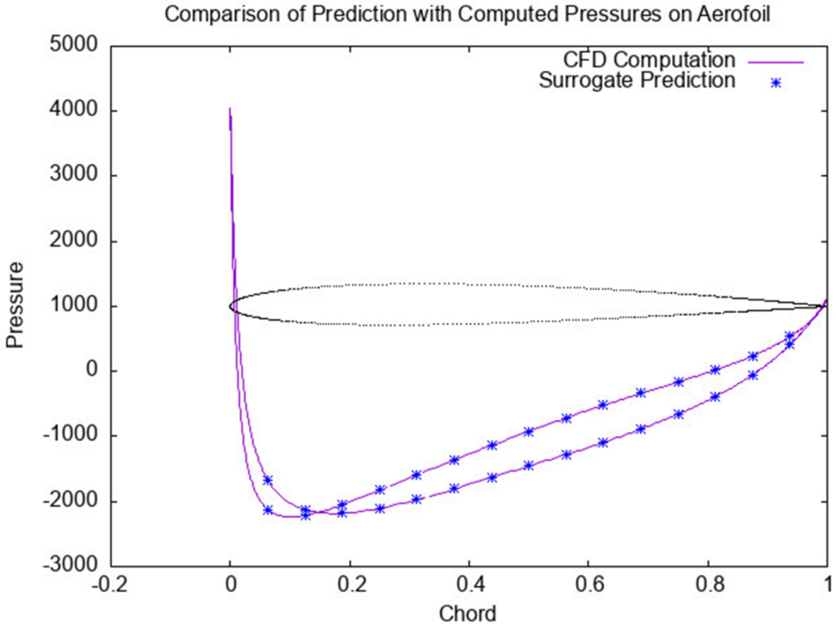

Figure 2: Comparison of surrogate model prediction and CFD computation of pressure distribution on a 2D airfoil section

The aerodynamic surrogate models are integrated into an aeroelastic analysis framework where predicted pressure distributions and force coefficients are coupled with structural models to determine static deformations under aerodynamic loading. The structural response is evaluated using a simplified, representative Beam Stick Model (BSM), as illustrated in Figure 3, with structural modes extracted from the BSM and corresponding load distributions used to compute deflections, twist, and overall deformed configurations.

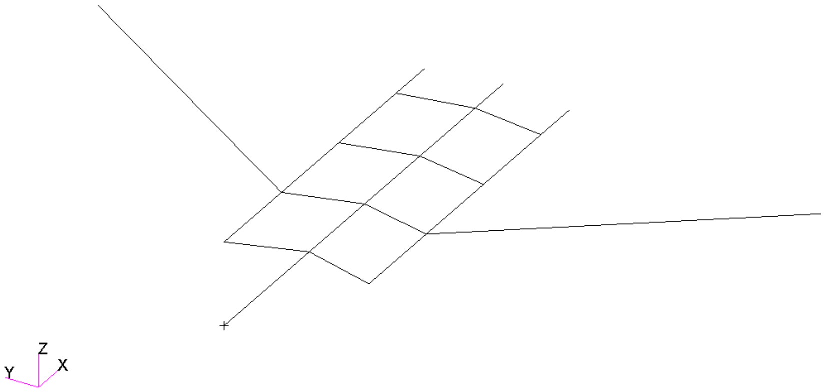

Figure 3: Beam Stick Model (BSM)

The coupling between aerodynamic loads and the structural response is formulated through a static aeroelastic equilibrium, which can be written as Equation 2.

$$K\delta = F_{aero}(x) - F_{inertia} \tag{2}$$

where K denotes the structural stiffness matrix, δ represents the structural deformation vector, F_{aero} is the distributed aerodynamic load vector predicted by the surrogate model, and $F_{inertia}$ is the inertia forces.

Rapid assessment of aeroelastic behaviour includes load redistribution due to structural flexibility and the computation of aerodynamic coefficients on the deformed shape. The geometric parameter-based approach ensures surrogate models adapt to configuration changes throughout the design space, providing consistent predictions across varying planform geometries characteristic of BWB aircraft.

Validation is performed through comparisons against established high-fidelity tools. Aerodynamic force coefficients and pressure distributions predicted by surrogate models are compared against full RANS CFD computations. Structural deformations and load distributions are validated against MSC Nastran FEA results. These comparisons quantify trade-offs between computational efficiency and prediction accuracy, demonstrating that the surrogate-based approach maintains sufficient fidelity for preliminary design while achieving computational speedups exceeding two orders of magnitude.

The effect of nonlinear aerodynamics in transonic regime becomes significant. Comparisons between linear aerodynamic theory, surrogate model predictions, and full RANS CFD computations show that in the subsonic regime, all approaches have a reasonable agreement. However, as flight conditions enter the transonic regime, significant deviations emerge [3]. The surrogate models, trained on CFD data including transonic cases, capture the shock onset effect and associated nonlinear pressure distributions with careful selection of geometry parameters in the machine learning dataset. In contrast, linear predictions increasingly diverge, failing to represent shock-induced pressure gradients and wave drag contributions. These comparisons demonstrate limitations of simplified models in transonic flow and validate the surrogate model's ability to approximate complex phenomena through data-driven learning.

The demonstrated deviations due to transonic effects have important implications for aeroelastic analysis of BWB configurations operating across broad speed ranges including transonic cruise. The approach enables designers to quickly evaluate hundreds of candidate configurations, mapping the design envelope while accounting for aeroelastic deformation, load redistribution, and performance impacts, facilitating more informed design decisions earlier in the development process.

References

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[2] Sung, N., et al., "BlendedNet: A Blended Wing Body Aircraft Dataset and Surrogate Model," arXiv:2509.07209, 2024.

[3] Sabater, C., and Görtz, S., "Fast Predictions of Aircraft Aerodynamics Using Deep-Learning Techniques," AIAA Journal, Vol. 60, No. 9, 2022.