# EFFICIENT NONLINEAR GUST LOAD PREDICTION ON HARW VIA A STATE-SPACE LIFTING LINE WITH NON-ITERATIVE HIGH-FIDELITY CORRECTION

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## EXTENDED ABSTRACT

## 1 INTRODUCTION

The design of future commercial aircraft faces a convergence of environmental and operational challenges that amplify the importance of unsteady, nonlinear aeroelastic effects. High-aspect-ratio wing (HARW) design is the current industry trend to further reduce fuel consumption of future aircraft and to progress towards environmental targets. These flexible structures exhibit geometric nonlinearities and lower natural frequencies, making them more vulnerable to atmospheric disturbances. At the same time, climate change is projected to increase the frequency and severity of atmospheric events such as clear-air turbulence (CAT) [1, 2].

Current industry-standard processes built around linear, frequency-domain methods like DLM cannot model significant aerodynamic nonlinearities and rely on late-stage high-fidelity corrections [3]. CFD time-domain simulations remain too costly for routine design and certification analyses. Therefore, a need exists for computationally efficient, time-domain methods capable of handling dominant nonlinear physics from early design stages.

## 2 METHODOLOGY

This work presents the implementation and validation of an enhanced state-space lifting line (SSLL) method.

The SSLL discretizes the wing into spanwise sections, each represented by an unsteady 2D state-space model coupled via a circulation model for 3D induced effects. This ODE-based formulation avoids the algebraic iterations of standard numerical lifting lines at each time step, and enables modular integration with dynamic stall models [4] or structural dynamics [5, 6]. While studies show SSLL can achieve accuracy comparable to mesh-based methods like UVLM [4, 7], its spanwise line discretization offers a significant computational advantage.

Barriety et al. [8] presented at IFASD 2019 the FNSA (fast nonlinear static aeroelasticity) method for efficient 3D nonlinear static calculation via high-fidelity data lookup tables. Later, Chandre-Vila et al. proposed an unsteady extension (uFNSA) [9] that applied the high-fidelity correction at each time step independently after the SSLL simulation, i.e., as an offline post-processing operation. This methodology is shown to fail when considering higher-frequency gusts on HARW geometries [10].

Building upon recent SSLL advancements, our method integrates:

1. A dynamic stall model, based on the SSLL formulation of Beyer et al. [4], that is integrated directly into the 2D sectional model.
2. A non-iterative, in-the-loop high-fidelity correction. Driven by the steady 3D high-fidelity aerodynamic database of the FNSA method, the discrepancy between the 3D lift distributions predicted by the SSLL and by the FNSA at the instantaneous effective angle of attack defines a target induced angle. A first-order filter governs the evolution of the model's induced angle state, driving it towards this target without requiring inner-step iterations, preserving the ODE formulation.

This paper focuses on the decoupled aerodynamic validation of the nonlinear gust loads on a rigid wing, serving as a precursor to a full aeroelastic simulation.

## 3 RESULTS AND VALIDATION

The method is applied to the XRF1-HARW at transonic cruise conditions (M = 0.85, $h$ = 35000 ft). Validation is performed against a dataset generated using CFD (CODA) simulations. The test cases for validation use the standard 1-cosine discrete gust to shape the vertical perturbation.

Preliminary results for standard 1-cosine gust encounters demonstrate that the HF-corrected SSLL significantly improves the prediction of peak loads and time-history shapes compared to the uFNSA and standard potential methods (DLM). Figure 1 shows the comparison of these methods for a case with a gust ratio of 0.15 and a reduced frequency of 0.17.

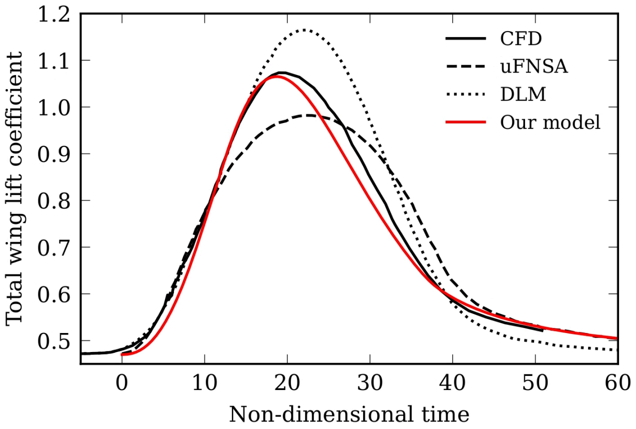

Figure 1: Comparison of lift coefficient response predictions for a 1-cosine gust encounter on the XRF1-HARW wing at M = 0.85 and h = 35,000 ft. CFD, uFNSA and DLM values extracted from Chandre-Vila [10].

## 4 CONCLUSION

To show the method's potential to address the future design challenges, it will be applied to a set of highly nonlinear scenarios, including large-amplitude gusts and a realistic, structured clear-air turbulence gust velocity profile. The final paper will present more validation cases across a matrix of gust gradients and intensities, providing quantitative error metrics (RMSE, peak load error) and computational speed-up factors relative to CFD or DLM. This sets the enhanced SSLL as a candidate model for de-risking the aeroelastic design of future flexible aircraft.

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