VALIDATION OF A NONLINEAR VORTEX-LATTICE METHOD FRAMEWORK FOR STATIC AEROELASTIC ANALYSES OF A FULL AIRCRAFT CONFIGURATION

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Abstract

Aeroelasticity has become an important driver for modern aircraft design, as the transition toward lighter and higher aspect ratio wings leads to more aeroelastic instabilities. For preliminary design, the development of efficient aeroelastic numerical tools remains a challenge. Low computational cost is required, but sufficient accuracy is also necessary to predict instabilities. The complexity of this problem mainly resides in the aerodynamic model. While the Doublet-Lattice Method (DLM) is widely used in industry for aircraft certification, it has certain limitations. An adapted Nonlinear Vortex-Lattice Method (NL-VLM) framework for aeroelastic analyses developed by Parenteau *et al.* [1] has shown great potential for industrial applications but has not been validated for a full aircraft configuration. This work aims to further extend the validation of this NL-VLM framework for a complete aircraft geometry by comparing aeroelastic results with those obtained with DLM and Reynolds-Averaged Navier-Stokes (RANS). This work focuses on the static aeroelastic phenomenon of control reversal.

1. Development of a Common Research Model - Bombardier

The Bombardier Research Aircraft Configuration (BRAC) is a classic T-tail business jet developed for the intended use of research and collaboration. Its control surfaces include ailerons, elevators and a rudder. The aeroelastic model of the BRAC was developed for this project to perform the aeroelastic analyses presented in this work.

2. Numerical Models

2.1. Structural Model

To perform aeroelastic analyses, the stick model of the BRAC was developed in Nastran format. Stiffness and weight distributions are applied to accurately represent the vibrational characteristics of the aircraft. Figure 1 presents the developed stick model of the BRAC.

2.2. Aerodynamic Models

This work presents aeroelastic results obtained from the use of the following aerodynamic models:

2.2.1. RANS

This is the highest fidelity method used in industry, and can capture compressibility, viscosity and thickness effects. Because of its high computational cost, it is not suited for preliminary aircraft design.

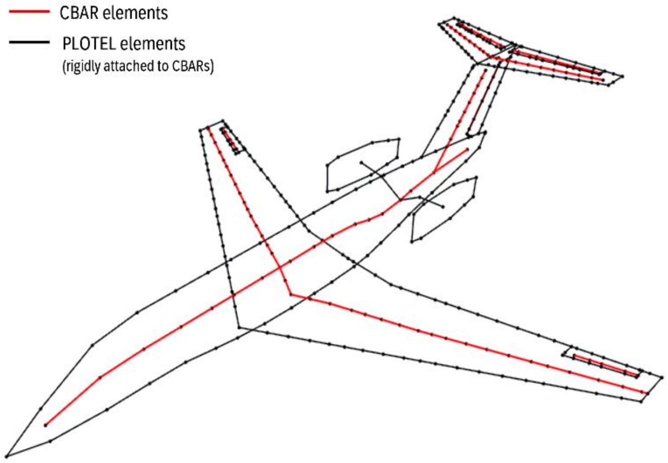

Figure 1. Stick model of the BRAC

2.2.2. DLM

This method [2,3] based on Linear Potential Flow Theory is widely regarded as the industry standard for aircraft certification, as its formulation in the frequency domain makes it well suited for stability analysis. However, the DLM cannot capture nonlinearities and is strictly limited to out-of-plane dynamics. The DLM is a low-fidelity model, but correction techniques have been developed and are commonly used in industry to account for compressible, viscous and thickness effects. A common correction method is the mapping of external high-fidelity solutions, such as 3D RANS, onto stripwise sections of the lifting surfaces to obtain DLM spanload distributions that match those of high-fidelity solutions. A correction matrix is computed and applied to the Generalized Aerodynamic Force (GAF) Matrix.

2.2.3. NL-VLM

VLM is also based on Linear Potential Flow Theory, but unlike the DLM, it has a time-domain formulation and naturally includes both out-of-plane and in-plane dynamics. The framework developed by Parenteau *et al.* proposes a classic Vortex-Lattice Method, with correction schemes to account for viscous and compressible effects, as follows. With the use of infinite swept wing databases obtained with RANS (2.5D), corrections are applied to the effective angle of attack of stripwise sections within the iterative resolution sequence. This allows resulting spanwise lift coefficients to match those of high-fidelity solutions, which include crossflow and transonic effects.

2.2.4. 3D RANS mapping

The coupling scheme used in this work differs from the 2.5D approach. Instead, 3D steady RANS databases are generated and reduced to 2D data by iterating the VLM until the obtained lift coefficient matches with 3D RANS data. These high-fidelity 3D databases are typically already available during conceptual design phases. They are also needed to apply corrections to the DLM, therefore no extra computational cost is incurred by their use for the NL-VLM. To obtain the reduced 2D databases, the following sequence is applied:

1. Compute VLM
2. Compute sectional inviscid lift coefficient for all stripwise sections ($C_{l\ \mathrm{inviscid}}$)
3. Compute "corrected" angle of attack for each stripwise section:
   $$\alpha_{\mathrm{local}} = \alpha_{\mathrm{local}} + \frac{C_{l\ \mathrm{3D\ RANS}} - C_{l\ \mathrm{inviscid}}}{2\pi}$$
4. Repeat steps 1-3 until the inviscid sectional lift coefficient is converged for an imposed tolerance ε:
   $$\|C_{l\ \mathrm{inviscid}} - C_{l\ \mathrm{3D\ RANS}}\| < \varepsilon$$
5. Compute effective angle of attack

This approach provides more accuracy at the wing root and tip than the 2.5D database approach for which the infinite swept wing assumption fails. Figure 2 shows that the resulting wing spanloads from the NL-VLM (coupled with a reduced 2D database) coincide with the 3D spanload distributions obtained with RANS. Through this reduced 2D database approach, sufficiently accurate aeroelastic predictions can be obtained for many different configurations earlier in the design process and allow for better optimization of aircraft geometry. Lastly, for aileron reversal analyses, the generated databases are obtained from the aircraft configuration with anti-symmetric deflections of the ailerons. This is required to properly simulate the flow during roll maneuvers.

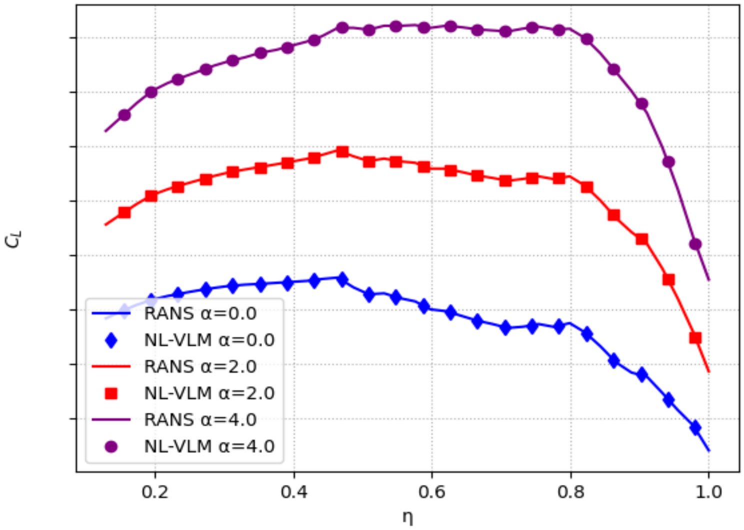

Figure 2. Spanload distribution of the BRAC wing at Mach 0.70

3. Results

3.1. Rectangular wing

Control reversal analyses are initially performed for a simple rectangular wing case presented in Andersen *et al.* [4], as shown in Figure 3. The aileron is placed at the ¾ chord and 50% outboard span. The structural model is a series of 8 beams of equal length, placed at 30% chord. No beam elements are added to model the aileron. DLM and RANS analyses are performed with commercial softwares Nastran and AeroSUITE respectively.

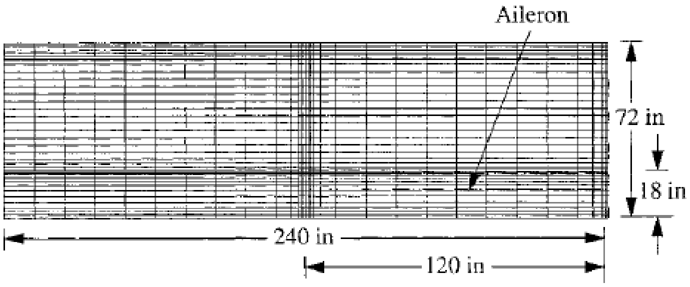

Figure 3. Rectangular wing configuration for control reversal analysis (source: [4])

Obtained dynamic pressures for aileron reversal are presented in Figure 4. Results show that for both low fidelity methods, VLM and DLM, reversal points coincide for all Mach numbers. The NL-VLM coupled with high-fidelity databases provides very similar results to those obtained with RANS.

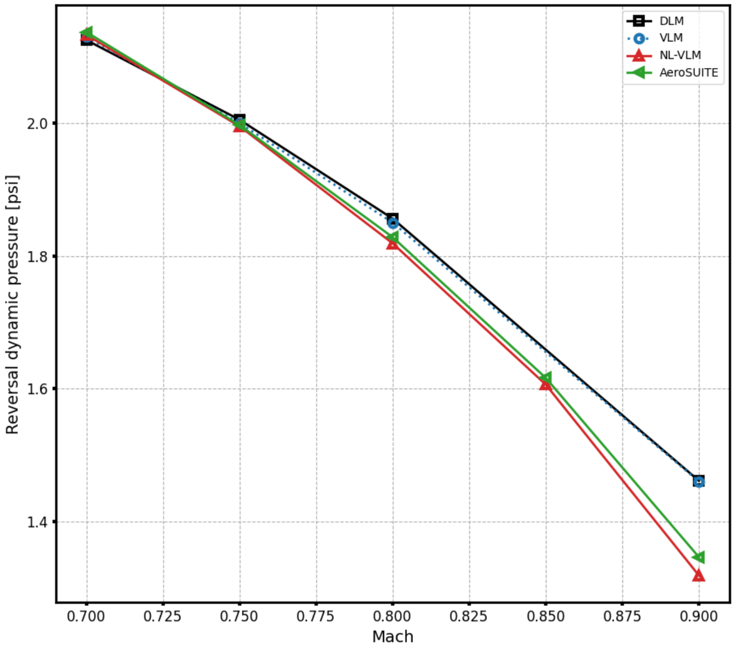

Figure 4. Reversal dynamic pressures for the rectangular wing configuration

3.2. Bombardier Research Aircraft Configuration

For the full aircraft configuration of the BRAC, most of the necessary data has been obtained and contains relevant information for the final paper.

4. References

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