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Efficient infinite-swept wing solver for steady and unsteady compressible flows

Matteo Franciolini [a], Andrea Da Ronch [b,*], Jernej Drofelnik [b], Daniella Raveh [c], Andrea Crivellini [a]

[a] Department of Industrial Engineering and Mathematical Science, Università Politecnica delle Marche, Ancona 60131, Italy
[b] Faculty of Engineering and the Environment University of Southampton, Southampton SO17 1BJ, UK
[c] Faculty of Aerospace Engineering, Technion, Haifa 32000, Israel

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A B S T R A C T

An efficient Navier–Stokes solver for the infinite-swept wing problem is presented. The new flow solution, that reproduces correctly the physics responsible for cross-flow effects, is obtained around a two-dimensional stencil. On the contrary, existing state-of-the-art methods rely on a three-dimensional stencil. Numerical details are followed by an extensive validation campaign, including steady and unsteady compressible flows. The test cases are for single and multi-element aerofoils in both laminar and turbulent regimes. Under identical conditions (numerical settings, grids, etc.), the computational cost of the proposed solver was reduced by at least 75% compared to that of existing state-of-the-art methods. This was also confirmed employing various turbulence models. With a limited effort required to enhance an existing computational fluid dynamics solver (either two or three-dimensional), the infinite-swept wing method was implemented in an industrial-grade package used across Europe for rapid engineering analysis.

1. Introduction

Industrial aircraft design proceeds through a series of maturity gates (MG). At the early stages of this process, designers explore a large parameter space relying heavily on empirical and linear correlations [1]. In order to down-select the final aircraft concept, the design parameters are tightened and addressed in ever increasing detail [2]. At MG 5, denoted "freeze of concept" in industrial jargon, the shape and structural layout are converged and the aircraft target loads are set. Design target loads are the limiting loads that an aircraft or aircraft component must be designed to withstand. The objective of MG 5 is to anticipate the certification loads level, and issue this data as target loads. It is critical to limit the risk in setting these target loads [3] because: a) if the target loads are underestimated, as revealed following flight test, then expensive re-design is often required incurring the costs and penalties arising from programme delay; and b) if the target loads are overestimated, the aircraft will be heavier than needed with degraded performances.

The analysis process to establish limit loads is computationally demanding as it consists of a very large number of conditions across the loads envelope. Despite a number of simplifications are introduced (linearised aerodynamics, weak coupling between disciplines, etc.), the number of load cases for certification [4], including ranges in Mach number, altitude, payload and fuel mass, exceeds easily several hundreds of thousands.

Today, the solution of the Navier–Stokes (NS) equations is recognised as a prerequisite for realistic flow applications, but the associated computational costs of the three-dimensional (3D) problem become prohibitive when confronted with the number of load cases. Therefore, researchers have proposed two stratagems to overcome this problem. The first stratagem concerns the approximation of the output quantities of interest, e.g. aerodynamic loads, across the design envelope exploiting efficient and accurate adaptive design of experiments [5] and surrogate modelling techniques [6]. The advantage is that the use of off-the-shelf computational fluid dynamics (CFD) packages is straightforward. The second stratagem consists of applying a number of simplifying assumptions in the solution of the NS equations, making calculations cheaper [7,8]. The advantage of this approach is the ability to find, for a particular problem, a balance between the approximation of the solution and the computational efficiency of the approximation. This work, specifically, addresses the second point.

* Corresponding author.
E-mail address: A.Da-Ronch@soton.ac.uk (A. Da Ronch).

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Nomenclature

b	Wing span, [m]
k	Reduced frequency
M	Mach number
$\mathbf{R}$	Rotation matrix
u, v, w	Velocity components, [m/s]
$\mathbf{V}$	Velocity vector, [m/s]
Re	Reynolds number
Pr	Prandtl number
$\mathbf{\Pi}$	Stress tensor
$\mathbf{S}$	Velocity gradients tensor
$\dot{\mathbf{q}}$	Heat flux vector

Greek

α	Angle of attack, [deg]
β	Side-slip angle, [deg]
Λ	Wing sweep angle, [deg]

Operators

:	double scalar product
$\otimes$	dyadic product

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
AR	Aspect ratio
CFD	Computational fluid dynamics
ISW	Infinite swept wing
LLT	Lifting line theory
MG	Maturity gate
NS	Navier–Stokes
NLF	Natural Laminar Flow
RANS	Reynolds-averaged Navier–Stokes
SA	Spalart–Allmaras
URANS	Unsteady Reynolds-averaged Navier–Stokes
VLM	Vortex lattice method

Indexes

$'$	Body-attached frame of reference
0	Mean value
A	Amplitude
∞	Freestream
:	double scalar product
$\otimes$	dyadic product

Rapid CFD methods currently employed in pre-MG 5 are derived combining Prandtl's lifting line theory (LLT) or the vortex lattice method (VLM), which are linear 3D aerodynamic methods, with a two-dimensional (2D) solution of the NS equations. The resulting aerodynamic predictive tool, often referred to as the quasi-3D method, is nonlinear because sectional flow nonlinearities are obtained from a 2D CFD analysis. As the LLT or the VLM are inexpensive, the overall cost of a quasi-3D analysis is comparable to that of a 2D CFD analysis. Reference [9] discussed the design process of the high-lift devices of an Airbus A380-like configuration and the relative challenges encountered in the development phase. The aerodynamic design was built around the quasi-3D method from the early stages of the design process to obtain a pre-optimised shape that was wind tunnel tested. Reference [10] exercised the quasi-3D method for the optimisation of a flexible high-lift wing configuration. Another application concerning drag minimisation was presented in Ref. [11]. Therein, the VLM was corrected with the MSES aerofoil predictions [12] based upon the solution of the Euler equations coupled with an integral formulation of the boundary layer equations, with a built-in transition model. The resulting tool was limited to low Reynolds number aerofoils. Other application areas of the quasi-3D method may be found in Refs. [2,13].

The reasons that the quasi-3D aerodynamic method finds large applicability for industrial design are: a) no detailed 3D geometry information is needed, relying instead on planform data and known aerofoil sections from available databases; b) minimum computational requirements, often not more than several hours of wall clock time for complete polars at various Mach numbers; and c) the easiness to introduce multi-physics considerations (icing, control sizing and allocation, etc.) without extra complication. It is worth observing that the references mentioned in the previous paragraph, and the references therein, rely on a 2D flow analysis to correct the predictions obtained from a linear 3D aerodynamic model. This is a poor choice in lieu of various experiments [14] showing that cross-flow effects, around a swept wing, strongly influence the boundary layer separation as well as the position of shock waves. Generally, these un-modelled effects are included via knowledge-based corrections, which are also a source of inaccuracies for less-conventional wing planforms departing from the original database.

This study is part of a larger on-going effort at the University of Southampton to deliver, within an industrial design environment, novel computationally efficient methods to calculate dynamic aeroelastic loads around complete aircraft. The aim of this work is to report on the development of a computationally efficient aerodynamic method suitable for aircraft preliminary sizing studies, improving upon existing state-of-the-art methods. The technical objectives are to: a) discuss the resolution of the NS equations for the specific problem of an infinite-swept wing (ISW) on a 2D grid stencil; b) present a thorough validation study of the proposed method for a number of steady and unsteady flow problems, using two different turbulence models; and c) demonstrate and quantify the performance gains for industry-relevant test cases. The proposed methodology has been implemented within the `DLR-Tau` flow solver, where it is referred to as the `2.5D+` approach to recall the enhanced (computational and convergence) properties in comparison with existing methods. To note that our work goes beyond that presented in Ref. [15] where steady-state flows are considered around simple configurations and an assessment of the performance improvements is missing.

Direct applications of the `2.5D+` solver within an industrial setting are the exploration of the flight envelope for a fixed configuration, including transient analyses when needed, and the optimisation of the aerodynamic shape (control effectors size and allocation, wing twist, etc.).

The paper continues in Section 2 with a brief overview of the CFD solver used in this work. Section 3 explains the underlying methodology and discusses the implementation details of the proposed flow analysis. Then, Section 4 focuses on results for steady and unsteady flow problems. Finally, conclusions are given in Section 5.

2. Flow solver

The flow solver employed in this study is `DLR-Tau` [16], a finite volume based CFD flow solver used by a number of aerospace industries across Europe. The `DLR-Tau` solver uses an edge-based

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