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AUTOMATED AERODYNAMIC MODEL GENERATION IN PRELIMINARY AIRCRAFT DESIGN

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Abstract

A scheme for the automated generation of aerodynamic 3D-panel models within an integrated preliminary aircraft design framework is presented. The described approach covers a wide range of configurations and allows for an explicit geometric representation of deployed high lift and control surfaces. The featured high lift devices encompass passive and active plain flap, fowler flap, slat and contour variable droop nose. The produced panel grids encompass structured and unstructured domains. This report summarizes the model generation process, the underlying data architecture, as well as external software used. An example case demonstrates the applicability of the model generation scheme to a multidisciplinary aircraft design analysis.

1. INTRODUCTION

The preliminary aircraft design problem is to find a feasible set of dependent and independent design variables exhibiting an optimum with respect to a given objective function. The design space is subject to restrictions imposed by a designated mission capability, regulations, environmental and economic considerations. A common objective function portraying economic performance is constituted by the direct operating costs. In order to evaluate the objective function a consistent set of dependent design variables is mandatory. This is achieved by an iterative consideration of all involved disciplines by dedicated analysis and design methods as shown in Figure 1. After a convergent set of dependent design variables has been found for a given set of independent design variables, objective function and restrictions are analyzed. This process is repeated for different combinations of independent design variables in order to identify optima in the design space. This approach has been implemented in various multidisciplinary design optimization (MDO) frameworks as the Computerized Environment for Aircraft Synthesis and Integration Methods (CEASIOM [1]), the Preliminary Aircraft Design and Optimization Program (PrADO [2]) or the conceptual aircraft design and synthesis code VAMPzero [3]. For a thorough summary of existing MDO-frameworks see [4].

The forecast of aerodynamic properties is an essential subdomain of the preliminary aircraft design process. These properties comprise global and local forces and moments, as well as pressure distributions for a set of flight cases. Due to various interdisciplinary direct and indirect relationships and the iterative nature of the design process aerodynamic properties affect the sizing of systems, propulsion, geometry, as well as the estimation of masses, flight performance, handling qualities and direct operating costs (DOC).

The contemporary aerodynamic analysis methods can be grouped into semi- empiricism (e.g. DATCOM [5]) and first principle based techniques. The latter comprise a variety of computational methods for fluid dynamics (CFD) obtained from the Navier-Stokes equations upon different assumptions regarding viscosity and vorticity. Among these vortex lattice [6], panel [7] and Euler [8] methods have been successfully employed within overall preliminary aircraft design processes.

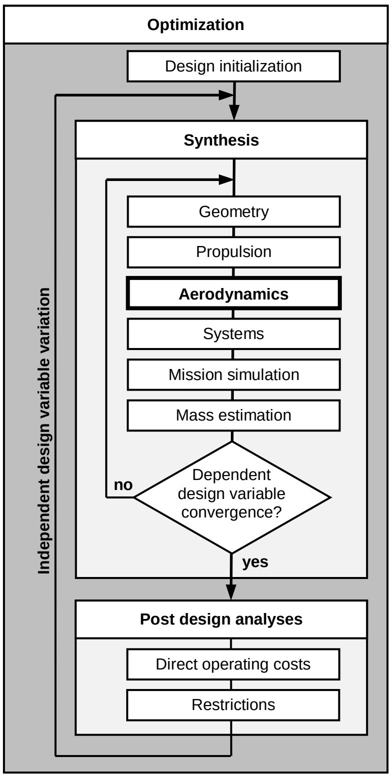


Figure 1. MDO-scheme of a preliminary aircraft design process.

Approaches towards the implementation of Reynolds-averaged Navier–Stokes methods (RANS [9, 10]) remain a challenge with respect to grid generation and computational cost.

The magnitude of the parameter space constituting a preliminary aircraft design problem, the iterative solution process and the challenge to asses many variants in a short period of time call for a low effort in model generation and computation. The high share of life cycle costs allocated in conceptual and preliminary design phases (≈85%) motivates a high forecast accuracy as a meaningful basis of decision-making [11]. The forecast accuracy depends on the scope of physical phenomena reflected by the respective analysis method and the level of depicted geometric detail. These objectives counteract each other as the effort in model generation and computation generally increases with the desired forecast accuracy.

This predicament has motivated the development of aerodynamic model generation schemes balancing both objectives. Current model generation schemes as SUMO [10] and OpenVSP [12] feature an integrated treatment of geometry and aerodynamic grid generation. They produce unstructured surface and volume grids for use with panel and EULER analysis methods.

This paper summarizes the efforts towards the development of an automated hybrid grid generation scheme for use with the panel method VSAERO and its integration into the MDO-framework PrADO. The presented approach covers a wide range of configurations and allows for an explicit geometric representation of propulsion arrangements and deployed high lift and control surfaces. This level of accuracy allows for the investigation of unconventional configurations, for which empirical aerodynamic data is not available [6, 13]. The featured high lift devices encompass passive and active plain flap, fowler flap, slat and contour variable droop nose.

2. MULTIDISCIPLINARY OPTIMIZATION FRAMEWORK

The MDO-framework PrADO has been introduced in the early 1990s and is under continuous development ever since. An arrangement of design modules maps the preliminary aircraft design process as depicted in Figure 1. Each module covers a discipline specific design or analysis task. The modules are written in Fortran and transfer data exclusively via a data management system accessing a set of databases. For several design and analysis tasks PrADO provides a choice of modules containing methods of varying fidelity. This flexible architecture allows for an individual layout of the design process and the integration of new methods. In the past various unconventional aircraft designs have been investigated with PrADO. The validity of the MDO-framework has been demonstrated for several conventional aircraft designs [2, 7, 14, 15]. In preparation of the aerodynamic model generation scheme presented in this paper the PrADO code has been translated to be used with Intel Fortran compilers. This allows for the use of Fortran standard 2008 features as object oriented data structures and a significant reduction of computation time. This reduction amounts up to 25% for a single design analysis run, i.e. determination of a converged set of dependent design variables for a designated set of independent design variables (see synthesis in Figure 1).

3. AERODYNAMIC ANALYSIS METHOD

Prior to this work model generation schemes for the multi-lifting-line method LIFTING_LINE [15] and the panel method HISSS [16] have been added to PrADO. The aerodynamic model generation schemes presented in this report produces models for use with the commercial 3D-panel code VSAERO by Stark Aerospace [17]. This panel method solves the Neumann problem of linearized potential flow by finding a solution for the perturbation potential ϕ on the problem surface *S* with the boundary integral equation (see Eq. 1).

$$(1) \qquad 2\cdot\pi\cdot\phi(p)+\int_{S-p}\phi\frac{\partial}{\partial n}\left(\frac{1}{r}\right)\cdot dS=\int_{S}\frac{\partial\phi}{\partial n}\frac{1}{r}dS$$

Here *r* is the distance from the point *p* where the potential is to be evaluated to an integration point on the body or wake surface. The velocity distribution on the body surface is found upon differentiation of the potential field. The Bernoulli equation and a Prandtl-Glauert compressibility correction yield the pressure distribution on the surface. The aerodynamic forces and moments are found by integration of the pressure distribution. By coupling the potential solution to a boundary layer model (Nash and Hicks, Drela [17]) viscous effects can be taken into account.

4. AERODYNAMIC MODEL GENERATION

The overall aerodynamic model generation scheme is summarized in Figure 2. Based on the PrADO geometry database and a set of input specifications an object oriented description of the boundary geometry is derived. The input specifications regard the choice of aircraft components to be meshed, the type of configuration (i.e. start, cruise, approach, landing), as well as the deflections of control, high lift and stabilizer surfaces. Moreover a symmetry specification decides on the generation of a half or full model. This allows for the investigation of lateral flight cases and a reduction of computation time for longitudinal cases. The object oriented geometry description is used to establish unstructured and structured grid domains. The resulting surface discretization is augmented with a wake description and translated to a master model in a format corresponding with the chosen analysis code. The master model is variable with respect to parameters not contributing to the surface geometry like angle of attack, angle of sideslip and Mach number, as well as thrusts and rotational rates of engines. Thereby a subset of few geometrical distinct cases out of the total set of flight cases of a complete aircraft design analysis is subjected to model generation. This allows for a significant reduction of computation time. The model generation is completed with a quality diagnosis by series of analysis runs checking for model errors. The following subsections cover the model generation steps in detail.

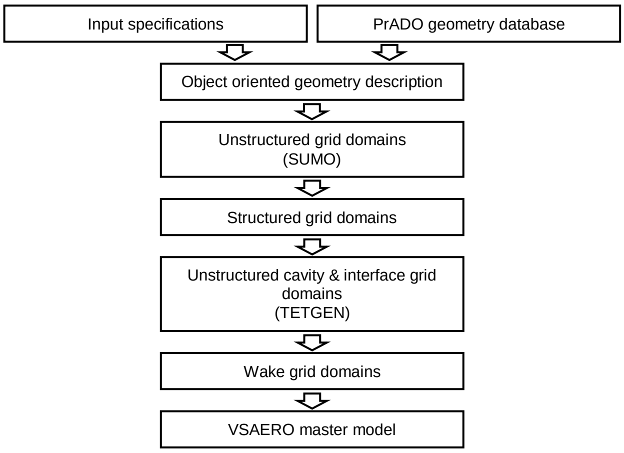


Figure 2. Aerodynamic model generation scheme.

4.1. Data Architecture

The PrADO geometry description is arranged as set of databases. Each database is associated with a specific aircraft component (e.g. fuselage, wing, nacelle) and is accessible by component specific routines. In order to simplify the model generation process, this concept is translated to an abstracted geometry representation. This abstraction views the aircraft as an aggregation of associated classes containing specific attributes and methods. The Figures 3 and 4 give a simplified view of this aggregation at different instantiation stages of the model generation process. For better comprehensibility several classes and derived classes are left out in both depictions.

At an initial stage this aggregation comprises the classes aircraft, surface, section and point (Figure 3). Each surface is associated with a component of the aircraft (e.g. wing, fuselage). The sections describe the outer contour of a surface as a sequence of points.

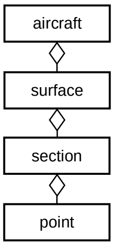


Figure 3. Class aggregation at initial instantiation stage.

At a final instantiation stage the surface class comprises unstructured and structured patch sets (Figure 4). A patch describes the discretization on a subdomain of a surface. An unstructured patch contains the faces (i.e. triangular surface elements) and corresponding vertices of an unstructured surface grid. A structured patch describes a quadrilateral subdomain of a surface as two or more sections. A section comprises regions consisting of point sequences. The region concept allows to subdivide a section into segments with an individual number and distribution of panel corner points.

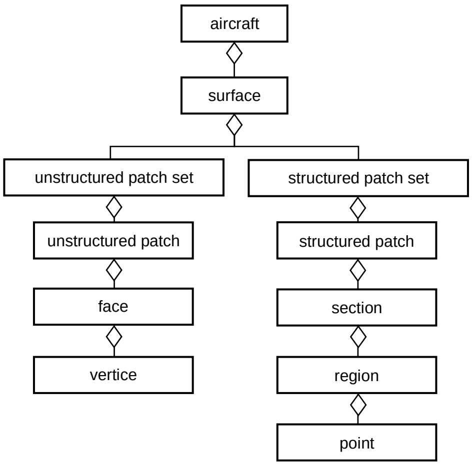
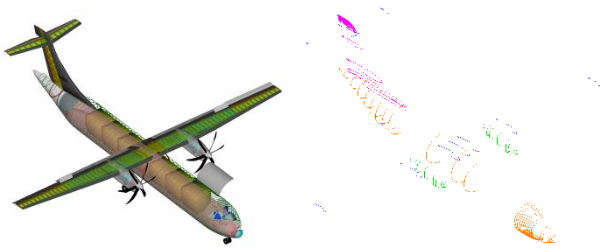


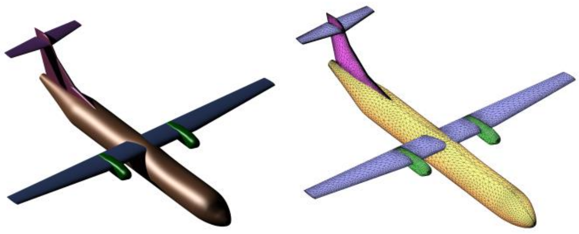
Figure 4. Class aggregation at final instantiation stage.

4.2. Unstructured grid domains

Based on the initial instantiation of the aircraft geometry as surfaces, sections and points an unstructured surface grid of the clean configuration is generated via an interface to the external surface modeler SUMO as exemplary shown in Figure 5. The resulting grid information is translated according to the unstructured patch set aggregation shown in Figure 4. The resulting grid produced by SUMO is generally not symmetrical to the longitudinal plane of symmetry. Therefore faces to one side of the symmetry plane are identified and mirrored to the opposing side. Moreover faces transgressing the symmetry plane are replaced by symmetrical counterparts.



a) PrADO model. **b)** Surface sections.

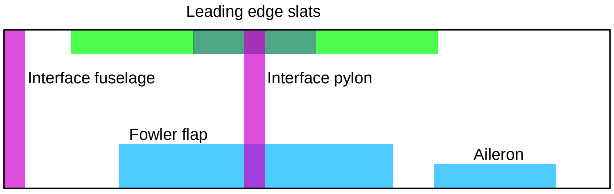


c) SUMO model. **d)** Unstructured grid.

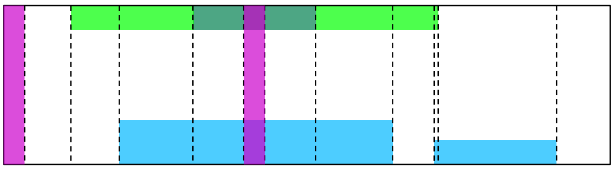
Figure 5. Unstructured grid domain generation via SUMO.

4.3. Structured grid domains

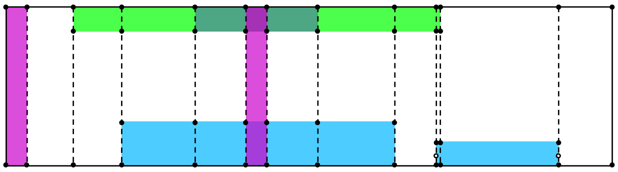
The structured grid domains comprise all lifting surfaces of the aircraft. For establishment of a structured grid these surfaces have to be subdivided into four sided boundary conform patches. In order to identify sections constituting these patches, the planform geometry, the location of movable surface domains corresponding with high lift and control devices and intersecting surfaces are considered.



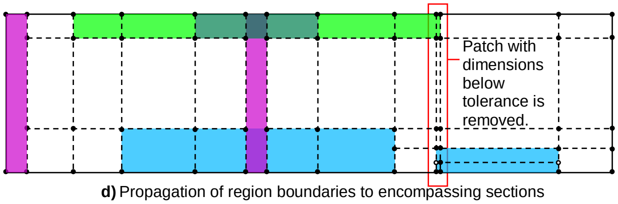
a) Wing top surface with different surface domains.



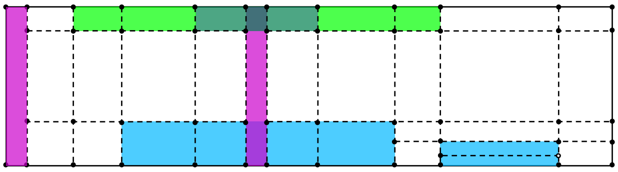
b) Establishment of patch boundaries (vertical dashed lines).



c) Establishment of region boundaries due to high lift and control surface deployment (black circles) and intersections of top with bottom surface (white circles).



d) Propagation of region boundaries to encompassing sections (horizontal dashed lines).

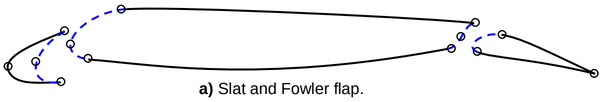


e) Final patch layout.

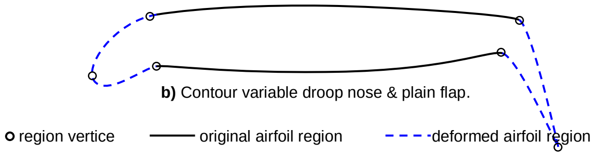
Figure 6. Subdivision of a wing surface into boundary conform patches.

In Figure 6 the subdivision of a top wing surface into boundary conform patches is show exemplarily. Based on the locations of interfaces to other surfaces, as well as high lift and control devices (a) the patch boundary sections are identified (b). The sections are further subdivided into regions corresponding with the chordwise extend of deployed leading and trailing edge high lift and control devices (black circles, c). Furthermore the deployment of high lift and control surfaces can cause intersections between top and bottom surface (white circles, c) also contributing to the region subdivision of a section. The region boundaries are propagated to the encompassing sections (d) of the surface. This process can result in very small patches. A filter algorithm removes these patches and incorporates the resulting gap in the remaining patch set, while preserving the original planform geometry (e). The process ensures that each section and region have no or one neighboring section and region, respectively. Moreover every section is divided into at least two regions accounting for the upper and lower side of an airfoil. The regions are described by cubic splines allowing for a continuous airfoil geometry representation with respect to first and second derivatives.

As only little information on the geometric data is present at the stage of preliminary aircraft design [18] airfoil deformations are developed upon parametrized descriptions according to the respective high-lift or control device type. The deformation schemes encompass slat, contour variable droop nose, plain flap, and Fowler flap as shown in Figure 7. The deformed geometries are derived from the clean airfoil geometry by as set of control points constituting cubic splines. The control point locations are specified by non-dimensional airfoil parameters. The deployment trajectories of Fowler flap and slat have to be specified explicitly.



a) Slat and Fowler flap.



b) Contour variable droop nose & plain flap.

Figure 7. Airfoil deformation schemes.

In Figure 8 the resulting patch and region layout for a wing with deployed high lift and control devices is shown. Multiple interfacing lifting surfaces require the propagation of region boundaries beyond the involved individual surfaces, as shown for a T-tail empennage (see Figure 9).

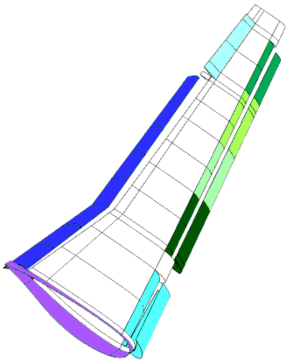


Figure 8. Patch subdivision of wing surface with deployed high lift and control surfaces.

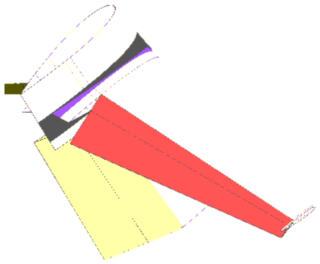


Figure 9. Patch subdivision of T-tail empennage with deployed control surfaces.

4.4. Discretization

Following the establishment of patches and regions panel corner points are distributed. In regions of high curvature an increased panel density is desirable to capture strong solution gradients. Therefore panel corner points are distributed according to a cosine function within in a region. This results in an increased panel density towards the vertices of region, which generally correspond with the location of leading or trailing edge, or an airfoil deformation due to the deployment of a high lift or control device. Moreover it is ensured that the spacing of panel corner points at the trailing edge lower side matches with the upper side. It has been shown that a matched spacing is beneficial to the satisfaction of the Kutta-condition [17].

At this stage the intersections between structured and unstructured domains (e.g. wing-fuselage intersection) exhibit nonconforming grid interfaces. An algorithm replaces the surrounding faces of the unstructured grid in these areas with a conforming grid. Moreover the tips of a lifting surface, as well as the tips of a deployed high lift or control devices expose holes in the surface grid. The regions constituting the fringes of these holes are identified and closed with an unstructured grid. In the above cases the tetrahedral mesh generator TetGen [19] is used for generation of the unstructured grid domains.

The grid generation is completed with the establishment of the wake discretization and several analysis runs checking for a correct surface and wake geometry specification.

The robustness of the aerodynamic model generation process is checked on several aircraft designs throughout its development (see Figure 10). The successful generation of watertight unstructured grid models via SUMO (see section 4.2) has been demonstrated on all of the displayed aircraft. In some cases this required a modification of the PrADO input geometry or specific grid generation parameters. For the designs marked with a dot working VSAERO models in start, cruise and landing configuration have been produced. In Figure 11 calculated pressure distributions on a choice of exemplary cases are shown.

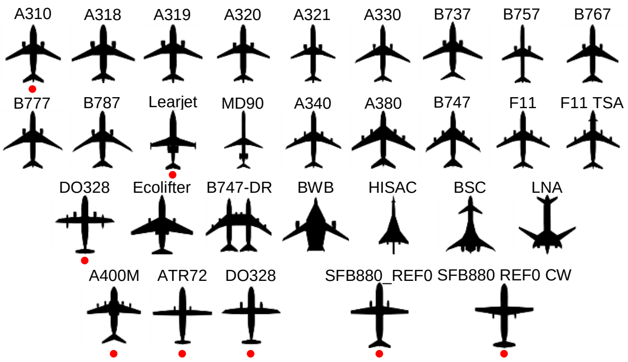
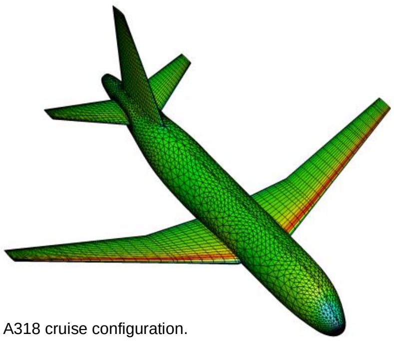
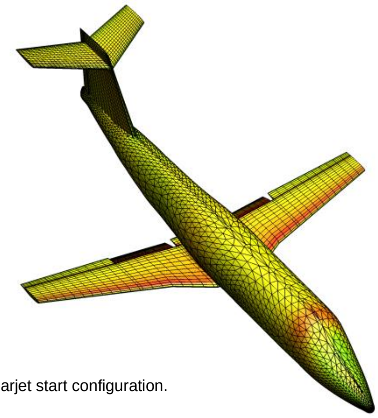


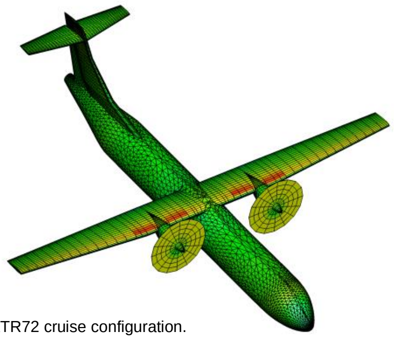
Figure 10. Aircraft geometries investigated for unstructured and unstructured grid generation (dot).



a) A318 cruise configuration.



b) Learjet start configuration.



c) ATR72 cruise configuration.

Figure 11. Pressure distributions on exemplary cases.

5. ANALYSIS METHOD VALIDATION

The aerodynamic analysis method VSAERO has been validated for a wing-fuselage high lift configuration [13]. The high lift devices comprise upper surface blown plain flaps with deflections up to 65° (see Figure 12). For comparison the same configuration has been calculated with the RANS method TAU [20]. The panel method solution was obtained without use of a boundary layer model.

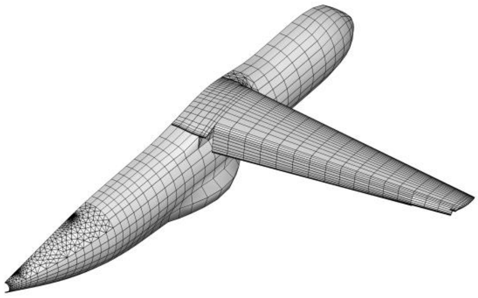


Figure 12. High-lift configuration.

In Figure 13 lift coefficients over angles of attack are shown, as obtained by both analysis methods. The panel code overestimates the lift by about 4% compared to the RANS solution.

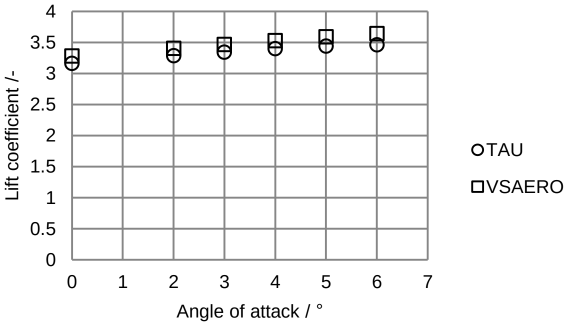


Figure 13. Lift coefficients over angles of attack for analysis methods VSAERO and TAU.

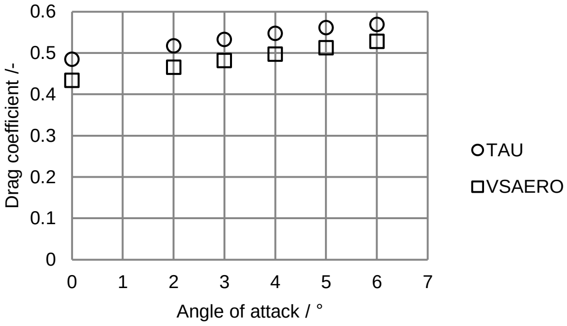


Figure 14. Drag coefficients over angles of attack for analysis methods VSAERO and TAU.

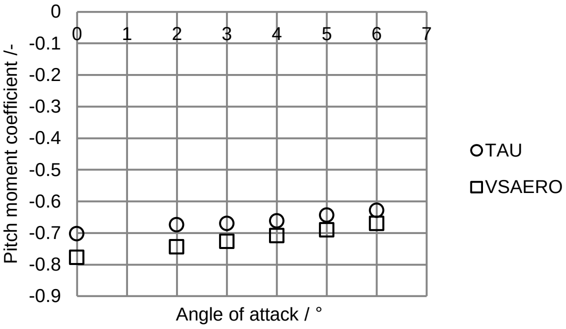


Figure 15. Pitch moment coefficients over angles of attack for analysis methods VSAERO and TAU.

In Figure 14 the corresponding results for the drag coefficient are shown. The panel code underestimates the drag by about 10% compared to the RANS solution. This deviation reflects viscous effects not included in the potential solution. In order to capture the share of friction drag in total drag the example case presented in the following section uses an empirical method by Hoerner [21]. In Figure 15 pitch moment coefficients over angles of attack are shown. The corresponding VSAERO result deviates by about 9% from the TAU solution.

6. EXAMPLE CASE

To demonstrate the presented aerodynamic model generation scheme in the context of a full aircraft design analysis a twin turboprop driven aircraft has been investigated (see Figure 16). The designated mission capability and resulting dependent design parameters are shown in Table 1.

In order to reduce the computation time only wing and horizontal tail plane are considered by the aerodynamic model. For computation of friction drag a method by Hoerner has been employed [21]. In order to calculate the required aerodynamic force and moment coefficients 30 geometric distinct models representing different combinations of configuration and horizontal tail plane deflection were created within 13 minutes.

Figure 16. PrADO aircraft design of twin turboprop aircraft.

Design parameter	Unit	Value
Range	km	2,000
Max. Payload	kg	12,000
Cruise Altitude	km	10.6
Cruise Mach number	-	0.6
Max. thrust (ISA,SL)	kN	211.718
Propulsion Mass	kg	3,909
Operational empty weight	kg	30,304
Maximum Fuel mass	kg	13,786
Maximum takeoff weight	kg	47,470
Takeoff distance (SL)	m	1,125
Landing distance (SL)	m	1,179

Table 1. Design parameter overview.

The required combinations of configuration, Mach number, angle of attack and HTP-deflection yield a total number of 5,800 cases, which have been calculated within 3 hours. A convergent design was found within 8 iterations. The total computation time amounts about 5 hours. The design analysis was run on a Intel-Core-i-7 with 8 GB RAM.

7. CONCLUSION

A scheme for the generation of aerodynamic models for a 3D-panel method has been presented. The scheme is integrated into the MDO-framework PrADO. Based on an abstract object oriented geometry description structured and unstructured surface grid domains are developed. For generation of the unstructured domains the surface modeler SUMO and tetrahedral mesh generator TetGen are used. The structured domains are developed upon a concept viewing the corresponding surfaces as quadrilateral patches described by sections, which are further broken down into regions. The region concept and the use of cubic splines enable the explicit representation of high lift and control devices. The model generation scheme is successfully demonstrated on the multidisciplinary design of a twin turboprop driven aircraft. Future development efforts focus on the use of a boundary layer model coupled to the potential solution for calculation of friction drag. Moreover a use of the model generation scheme and the chosen panel method for calculation of aerodynamic loads in a finite element method (FEM) based mass estimation process is envisioned.

8. ACKNOWLEDGEMENTS

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