RAPID DESIGN OF UNCONVENTIONAL AIRCRAFT USING SOFTWARE TOOLS COUPLED IN OPTIMIZATION LOOP – LESSONS LEARNED

Tomasz Goetzendorf-Grabowski[1], Agnieszka Kwiek[1], Jacek Mieloszyk[2] & Andrzej Tarnowski[1]

[1]Warsaw University of Technology, Institute of Aeronautics and Applied Mechanics,
Nowowiejska 24, 00-665 Warsaw, Poland
[2]Łukasiewicz Research Network – Institute of Aviation,
Krakowska 110/114, 02-256 Warsaw, Poland

Abstract

The paper presents the experience gained while designing aircraft in unconventional configuration using a methodology based on multidisciplinary optimization. An outline of the method involving the addition of dynamic stability analysis at an early design stage is presented. Several examples of aircraft designs with unconventional configurations using self-developed and validated in flight software were shown.

Keywords: unconventional configuration, optimization, panel method, stability, MDO

1. Introduction

The design of new aircraft, especially in unconventional configuration [1, 2], is always a challenge. It is very important to maintain a good balance between high performance parameters and flying qualities. Classical project spiral, that covers all disciplines considered in the design process, usually requires many iterations, which takes time and money. To reduce design costs, it is necessary to take into account most disciplines, especially stability analysis. This was a topic of many projects, e.g. SimSAC [3]. Automating the design process was the next stage of work [4]. This involved the need to couple software tools in a feedback loop [5, 6], where the key element is the optimization application [7].

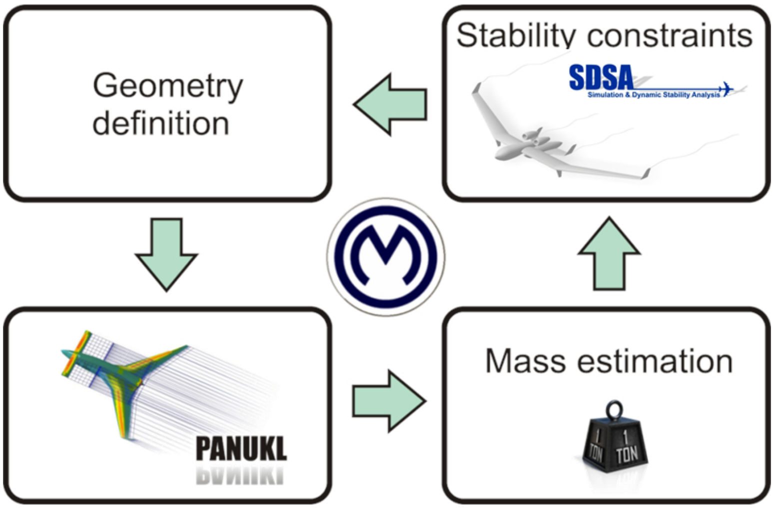

Figure 1 – The optimization loop scheme

On the initial stage of the aircraft design low fidelity numerical tools are the most effective, because they offer results of satisfactory precision and low computational cost [8]. It is the most beneficial

when multiple configurations have to be analyzed, for instance in an optimization process. This paper shows the comparison of computations results with measured real life data for different aircraft, all designed in unconventional configuration including a tailless aircraft, join wing, and canard. For computations, authors used their in-house codes coupled in optimization loop (Figure 1).
The PANUKL package [9] where it's main component is low order potential flow solver software is dedicated to aircraft aerodynamics computation (see example: Figure 2 and Figure 3). Moreover, it includes the function of preparing data for Finite Element Analysis in Calculix [10], data for dynamic stability analysis in SDSA [11, 12], and a tool for estimating mass properties [13].

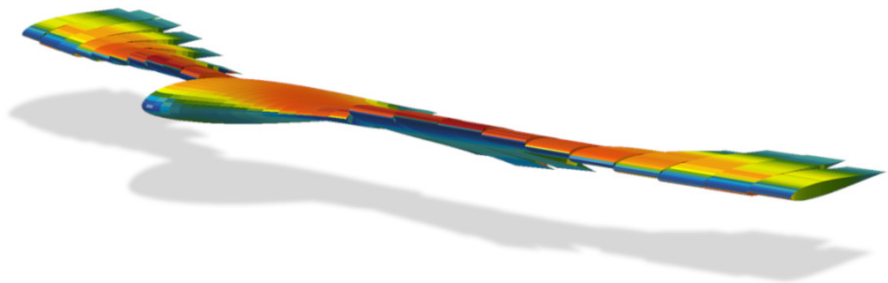

Figure 2 – Example of the pressure distribution computed by the PANUKL of the aircraft designed as a morphing flying wing [14].

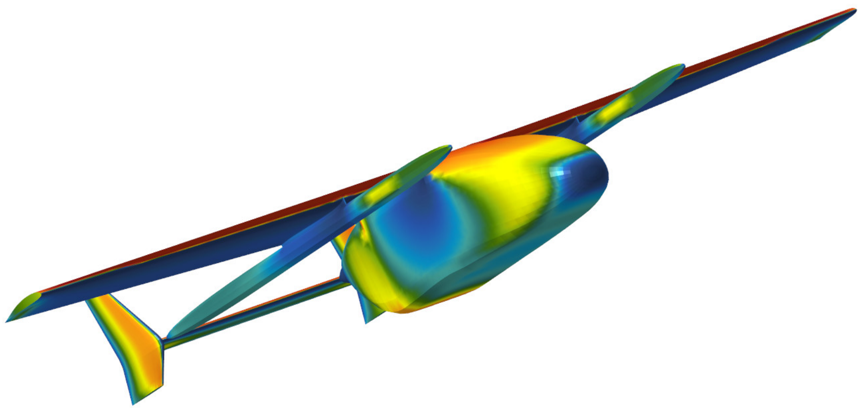

Figure 3 – Example of the pressure distribution computed by the PANUKL of the VTOL aircraft [15].

Solving an optimization problem on the preliminary stage of design is a common approach to obtain aircraft geometry that meet certain set of requirements. Usually, those requirements impose of solving a multidisciplinary problem [16–19]. Such approach to advanced preliminary design process is defined as Multidisciplinary Desing Optimization (MDO). Combining dedicated software responsible for computing aircraft geometry and its aerodynamic response, with structural and mass analysis allows for advanced dynamic stability investigation. The optimum solution found by simultaneous use of all these disciplines by exploiting their interaction guaranties best possible design. Using our in-house dedicated software OptiM for automated process optimization, during aircraft design, tens of thousands of different geometric configurations with multiple constrains can be analysed in mater of days, in search for the best candidate which satisfies design requirements.

1.1 PANUKL

PANUKL is the package to be used for aerodynamic computation of an aircraft, using low order panel method [20]. The package has over 20 years history. Beginning in 1994, the first version of the preprocessor, computation programs, and presentation software was completed in 1996 and named PANUKL 96. This version worked under MS-DOS system.

The first version of PANUKL package in windows architecture was created at the turn of 2001-2002 and was designed to work on both MS Windows and Linux. The major functional change was to create a program that was a part of both a pre- and post-processing and was the main program for managing the package as well. However, it was still possible to run package programs from the command line to maintain compatibility with the previous version as far as possible and to allow individual computations to be combined in the optimization process. The scheme of typical one case computation is presented in Figure 4.

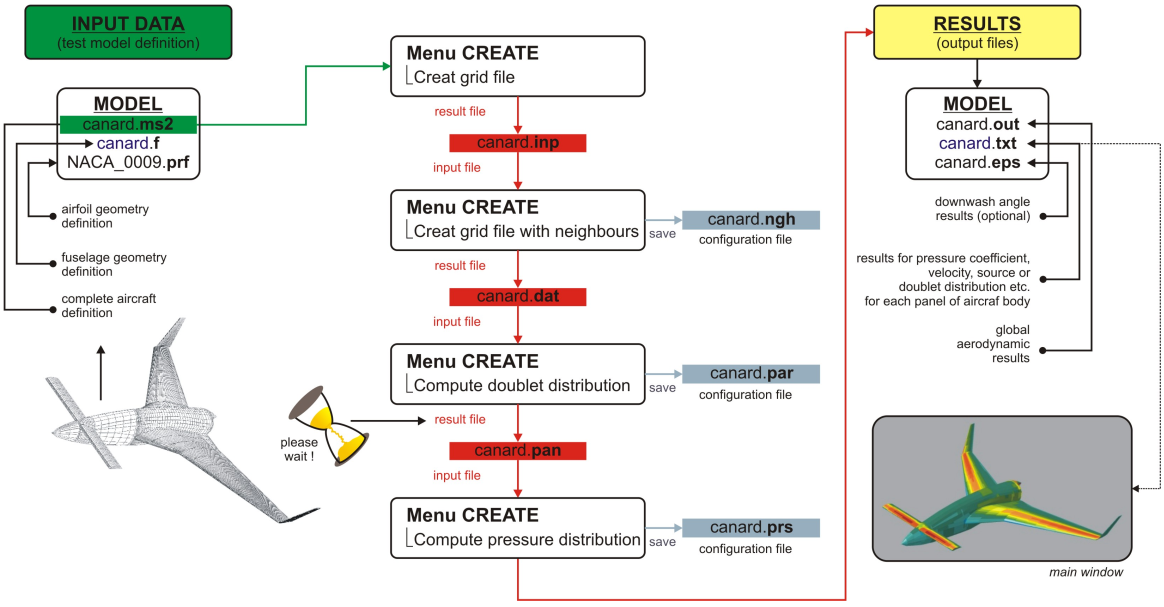

Figure 4 – Data flow in PANUKL

The package was initially validated by comparing computational results with data given from widely recognized reports such as NACA TR-824 [21] (Figure 5), Hess' original paper [22] and other studies [23] (Figure 6). The validation results were presented in [24], while the first results of stability characteristics were presented in [25].

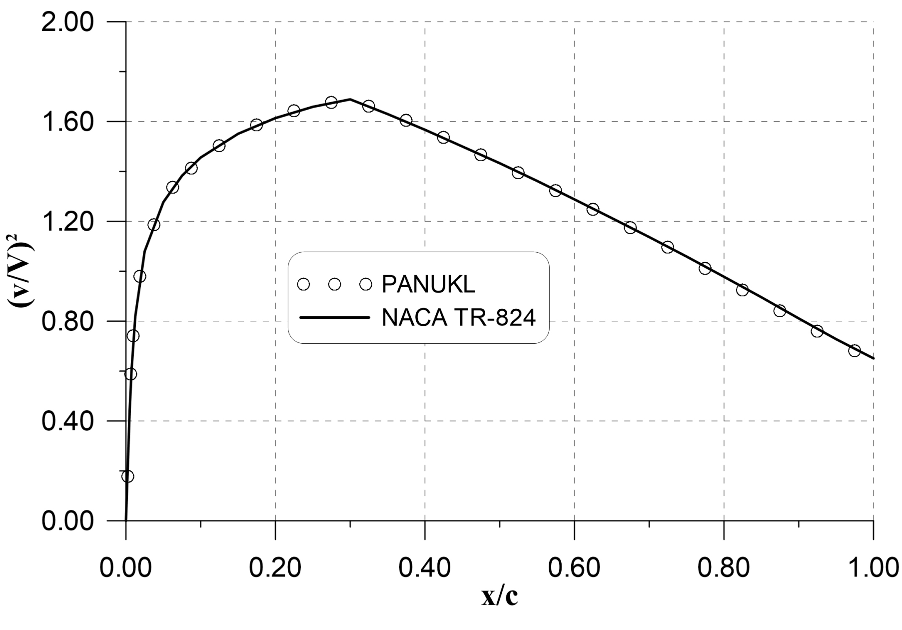

Figure 5 – Chordwise distribution of air flow velocity around a rectangular wing (AR=10, AoA=0 deg), airfoil NACA 63-4-020

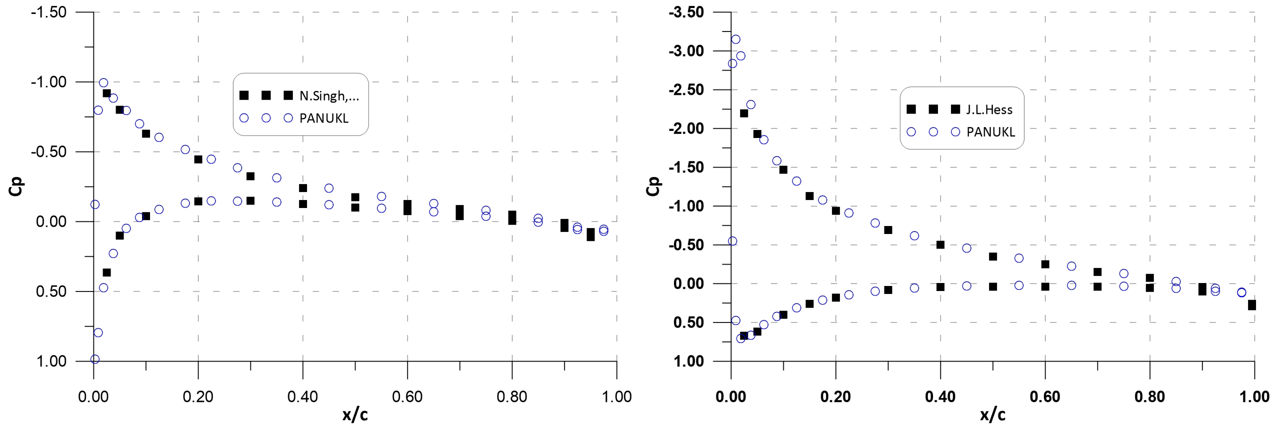

Figure 6 – Chordwise (2y/b=0.9) Cp distribution (NACA 0012) for:
rectangular wing, AR=2.4, AoA=6 deg (left)
tapered wing, AR=4.8, taper ratio λ=0.5, sweep ν_{LE}=30 deg and AoA 10 deg (right)

Real validation requires comparison with experimental results, usually with data from wind tunnel tests, or at least with the results of more advanced methods (Euler, Navier-Stokes). The results of the basic aerodynamic characteristics obtained for a small rocket plane are presented below (Figure 7). The results were compared with those of tunnel tests and the results of calculations obtained using the Euler [26] and Navier-Stokes methods [27]. The results show overall good compliance of the lift coefficient with worse convergence for the drag coefficient, which is understandable considering the simplicity of the flow model in the PANUKL package. Aerodynamic drag in fact consists of only two components, i.e. induced drag and pressure drag. Friction drag is added using a statistical approach [28]. The nature of the drag curve is satisfactory, as it is almost parallel to the experimental one.

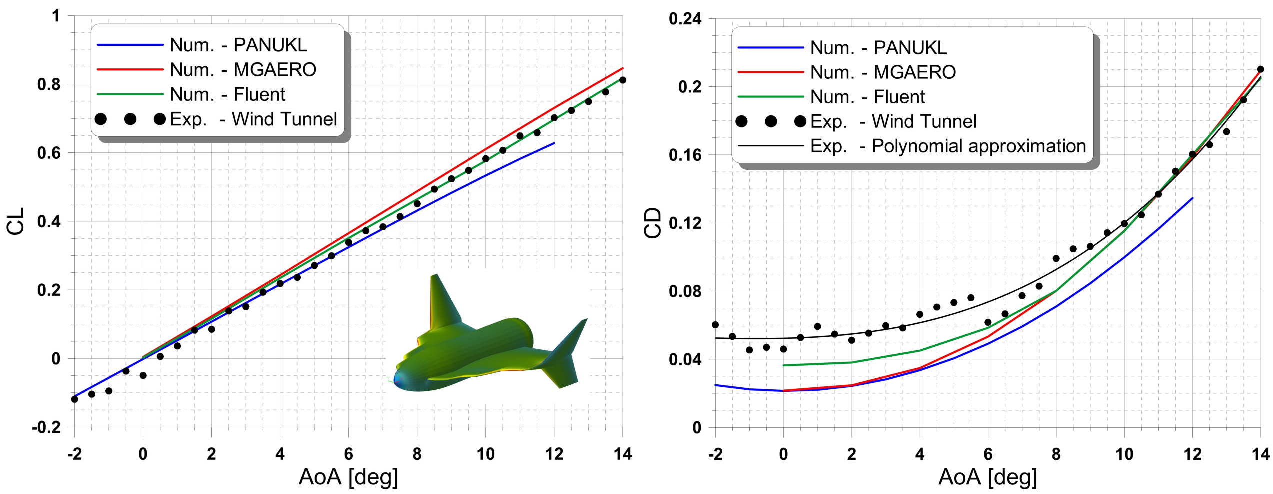

Figure 7 – Lift and drag coefficient of small rocket plane - comparison of methods

1.2 SDSA

SDSA is the package to be used for analysis of dynamic properties of an aircraft. Package was designed and developed within the SimSAC project [3] and initially was devoted to be integrated with CEASIOM environment [29]. The package uses a classic non-linear model of motion with 6 degrees of freedom, which, after linearization, allows the eigenvalues analysis. This analysis, when supplemented with eigenvectors, enables the identification of typical modes of motion. Since linearization is performed just when building the state matrix, numerical differentiation of the derivatives of the state vector was used, which enables numerical flight simulation using the same mathematical model and thus non-linear analysis. In both cases, aerodynamic characteristics can be represented in the form of classic stability derivatives as well as in the form of multidimensional tables containing data from various sources. Integrating SDSA with the PANUKL package (Figure 8) and adding the possibility of batch work made it possible to automate the calculations and use the stability criteria directly as optimization constraints [30].

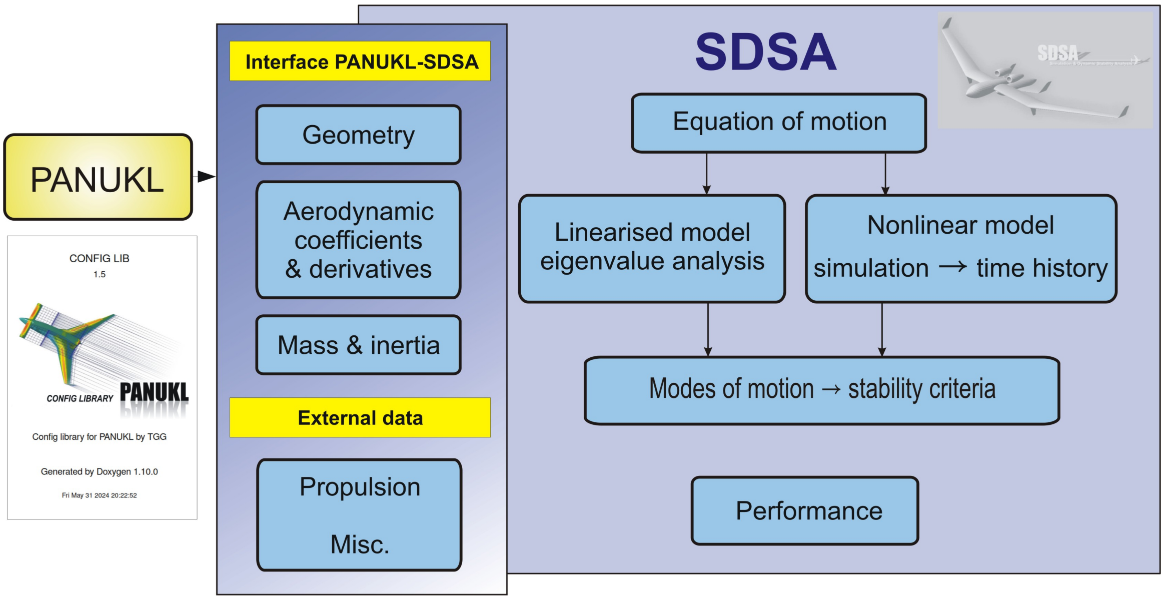

Figure 8 – Data flow in PANUKL-SDSA

1.3 OptiM – Optimization Software

The optimization software named OptiM [7] drives the automated design. It is general purpose software allowing to define optimization task for any discipline, also multidisciplinary optimization. It offers eight optimization algorithms. Three of the algorithms are deterministic with four different direction search methods for the gradient algorithm. Five remaining algorithms are heuristic, including Genetic Algorithm and Particle Swarm Optimization (PSO) methods. Features of the OptiM include graphical interface for user to setup optimization process like input variables, optimization algorithms parameters, or quickly shift between used optimization algorithms. The software also prints and plots optimization results and offers few statistical tools for post-processing of the results.
The research team used OptiM in number of project for coupling the structure analyses, fluid dynamics analyses, mass analyses, dynamic stability analyses and conducting multidisciplinary optimization. The goal of the optimization was to improve flight performance indicators like range, or endurance while satisfying multiple constrains including superior flight dynamics stability constrains. It is unique to include full dynamic stability characteristics and constrains in the conceptual and advanced preliminary design process together with good flight characteristics, but it is crucial aspect of the efficient aircraft design. OptiM proved successful in many projects, including the ones presented in the paper.

2. Aircraft RAPID DESIGN

Rapid design in optimization loop is achieved not only due to the fast operation of the low order aerodynamic solver in the PANUKL package, but above all thanks to the built-in interface [31] that allows significant changes to the aircraft geometry in batch mode.
Proven optimization algorithms such as Particle Swarm Optimization (PSO) used by in-house software search for the optimal solution for dozens of parameters describing the detailed geometry of the aircraft, in particular the lifting surfaces. The software is also adapted to parallel computing, allowing any number of geometries to be tested simultaneously in a single loop iteration, depending only on the number of logical processors on the computer. The flexible structure of the package additionally allows to solve inverse problems, such as searching for a geometry with the given span-wise distribution of the lift force.

The presented design environment has been proven in subsequent aircraft designs with unconventional layouts, including the canard configuration, TSA (three surface aircraft), flying wing, delta wing and box-wing. The selected examples are presented below.

2.1 Three Surface Aircraft – AT-6

The first example is Three Surface Aircraft (TSA) designed and developed in a small company (AT-P AVIATION). This is a 4-seat, twin engine light aircraft, which was well described in [32]. The application of the software tools mentioned above allowed to decide to change geometry of the main wing (dihedral angle) and vertical tail to ensure correct handling qualities, especially to improve Dutch roll characteristics. The flight tests of scaled unmanned demonstrator successfully validated the computing results - Figure 9. The full-scale aircraft is being prepared for its maiden flight.

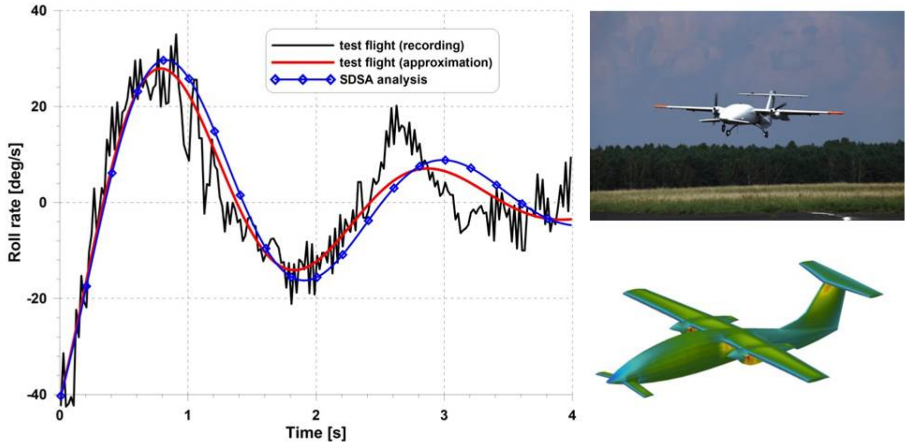

Figure 9 – AT-6 - Dutch roll test – comparison computational results and test flight data.

2.2 Flying wing - NORD

The flying wing configuration was designed and developed within the project NORD (Numerical Optimization Results Demonstrator). It is a small size reconnaissance UAV with electric propulsion. The configuration was validated during the flight test campaign. The recorded parameters proved the results of computation and the pilot's opinions were consistent with computed handling qualities [33]. The selected results are shown in Figure 10.

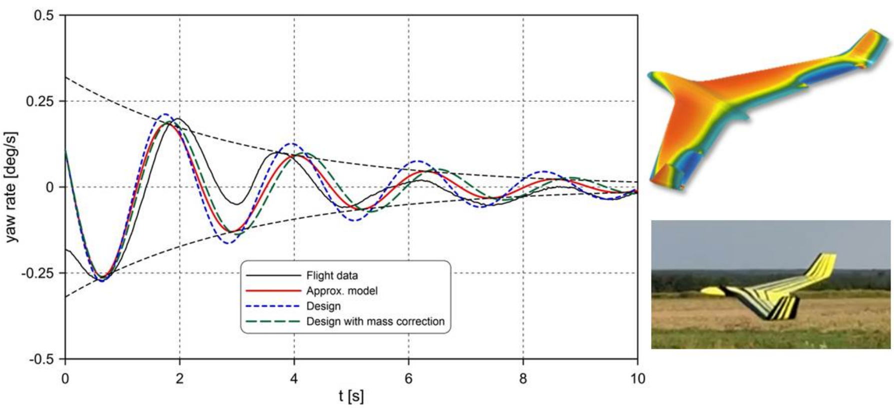

Figure 10 – NORD – Dutch roll test – comparison computational results and test flight data.

2.3 Box wing

The presented example of box-wing configuration was designed and developed within the MOSUPS project. A methodology similar to the one tested within NORD project was applied [30]. The analysis allowed to find the appropriate position of gravity center versus both wings configuration (sweep angle, twist distribution and relative position: stagger and gap) to satisfy good flying qualities. The selected results of dynamic stability analysis of the final version are shown in Figure 11.

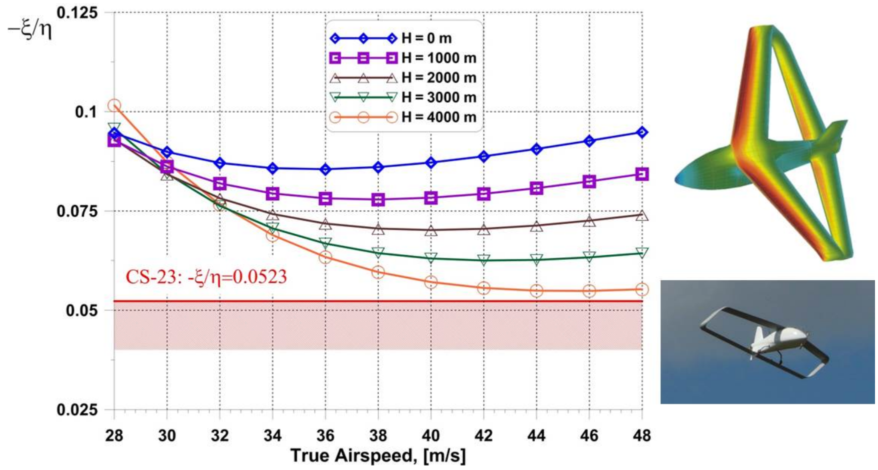

Figure 11 – Box-wing – Dutch roll characteristics against the background of CS-23 stability criterion.

2.4 Canard configuration

The presented example of canard configuration was designed and developed within the own author's project [34]. As it was designed four decades ago the current methods were not applied. Project required to test numerous configurations and Figure 12 presents a part of stability analysis - test of Dutch roll sensitivity on dihedral angle. The analysis has now been repeated using the methodology described above and the satisfactory results were obtained saving time and effort.

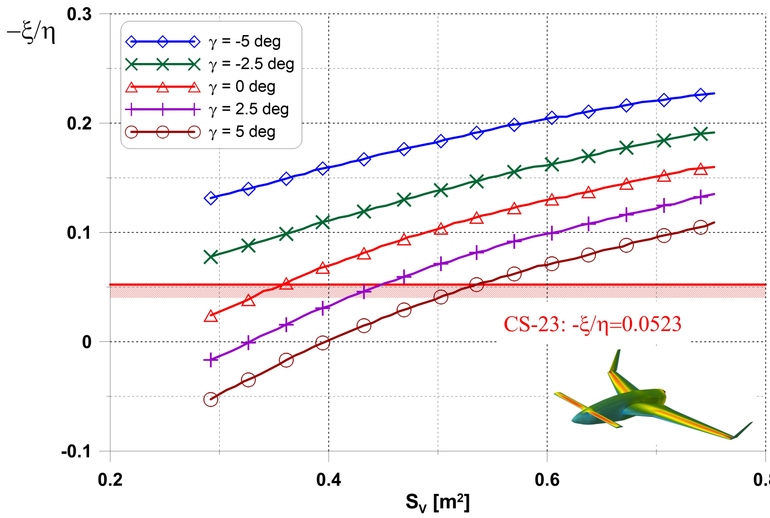

Figure 12 – Canard – Dutch roll characteristics against the background of CS-23 stability criterion for different dihedral angle.

3. Summary

The presented examples show the usefulness of the methodology described above. Computations accuracy is emphasized in terms of usefulness for aircraft design. Properties prediction such as aerodynamic characteristics, mass of the structure, and flight dynamic characteristics are essential.
This article presents the advantages and effectiveness of designing and building aircraft in the MDO process using low fidelity numerical tools dedicated to aerodynamic, structural, mass and dynamic stability analysis. Thanks to the effective combination of this process with a program for parametric aircraft geometry design, it was possible to automatically analyze thousands of geometric configurations in order to find the optimal solution that meets the assumed efficiency criteria of the designed structure. The automatic search for a solution was possible thanks to our in-house software using advanced optimization algorithms, in particular Particle Swarm Optimization (PSO) allowing for parallel calculations, which significantly contributed to shortening the calculation time. It is worth emphasizing the ability of batch operation of all programs allowing automatic control of all specialized software

tools.

Despite the certain and inevitable inaccuracy of low fidelity numerical software tools, the obtained optimization results, after verification in advanced commercial solutions, perfectly met the assumed design criteria. As presented in the article, after wind tunnel testing, the designs were then validated in practice. The structures were built and underwent detailed flight testing. The collected flight data confirmed the previously obtained optimization results with high accuracy and showed very good flight parameters and flying qualities. It should be strongly emphasized that the designed structures were characterized by unconventional geometry, such as flying wing, box wing, delta wing or three surface aircraft, and therefore having complicated aerodynamics, which cannot be easily calculated using simplified aircraft design methods.

To sum up, the combination of advanced design methods such as MDO, combined with the effective use of low fidelity numerical multidisciplinary tools, allows for the quick and effective design of very advanced aircraft structures that meet high flight parameters criteria. The methodology and software tools developed by our team have been repeatedly validated in practice and, according to the authors, constitute one of the most advanced solutions for a comprehensive approach to the design of aircraft structures.

4. Contact Author Email Address

mailto: tomasz.grabowski@pw.edu.pl

5. Copyright Statement

References

[1] T. Goetzendorf-Grabowski and J. Mieloszyk. Unconventional configurations - Design and optimization. In *30th Congress of the International Council of the Aeronautical Sciences, ICAS 2016*.

[2] Tomasz Goetzendorf-Grabowski. Flight dynamics of unconventional configurations. *Progress in Aerospace Sciences*, 137:100885, February 2023.

[3] Arthur Rizzi. Modeling and simulating aircraft stability and control—the simsac project. *Progress in Aerospace Sciences*, 47(8):573–588, November 2011.

[4] T. Goetzendorf-Grabowski, J. Mieloszyk, and D. Mieszalski. MADO - software package for high order multidisciplinary aircraft design and optimization. In *28th Congress of the International Council of the Aeronautical Sciences*, 2012.

[5] Tomasz Goetzendorf-Grabowski. Multi-disciplinary optimization in aeronautical engineering. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 231(12):2305–2313, May 2017.

[6] Tomasz Goetzendorf-Grabowski and Jacek Mieloszyk. Common computational model for coupling panel method with finite element method. *Aircraft Engineering and Aerospace Technology*, 89(5):654–662, sep 2017.

[7] Jacek Mieloszyk. OptiM - Software package for numerical optimization. `https://www.meil.pw.edu.pl/add/ADD/Teaching/Software/OptiM`, 2020. (Accessed on 01/05/2024).

[8] Tomasz Goetzendorf-Grabowski and Agnieszka Kwiek. Study of the impact of aerodynamic model fidelity on the flight characteristics of unconventional aircraft. *Applied Sciences*, 13(22):12522, November 2023.

[9] Tomasz Goetzendorf-Grabowski. PANUKL - Package to compute the aerodynamic characteristics of an aircraft using low order panel method. `https://www.meil.pw.edu.pl/add/ADD/Teaching/Software/PANUKL`, 2020. (Accessed on 01/05/2024).

[10] CalculiX - A Free Software Three-Dimensional Structural Finite Element Program. `https://www.calculix.de`, 2023. (Accessed on 01/05/2024).

[11] Tomasz Goetzendorf-Grabowski. SDSA - Simulation and Dynamic Stability Analysis application. `https://www.meil.pw.edu.pl/add/ADD/Teaching/Software/SDSA`, 2020. (Accessed on 01/05/2024).

[12] Tomasz Goetzendorf-Grabowski, Dawid Mieszalski, and Ewa Marcinkiewicz. Stability analysis using sdsa tool. *Progress in Aerospace Sciences*, 47(8):636–646, November 2011.

[13] Jacek Mieloszyk, Andrzej Tarnowski, Tomasz Goetzendorf-Grabowski, Mariusz Kowalski, and Bartłomiej Goliszek. Comparison of different fidelity mass analyses. *Aircraft Engineering and Aerospace Technology*, 93(7):1229–1235, August 2021.

[14] Andrzej Tarnowski and Tomasz Goetzendorf-Grabowski. Design of morphing wing with surface discontinuity. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 232(14):2638–2650, August 2018.

[15] Tomasz Goetzendorf-Grabowski, Andrzej Tarnowski, Marcin Figat, Jacek Mieloszyk, and Bogdan Hernik. Lightweight unmanned aerial vehicle for emergency medical service – synthesis of the layout. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 235(1):5–21, March 2020.

[16] Abdelkader Benaouali and Stanisław Kachel. Multidisciplinary design optimization of aircraft wing using commercial software integration. *Aerospace Science and Technology*, 92:766–776, September 2019.

[17] Abdelkader Benaouali and Abdelwahid Boutemedjet. Multidisciplinary analysis and structural optimization for the aeroelastic sizing of a UAV wing using open-source code integration. *Aircraft Engineering and Aerospace Technology*, 96(4):585–592, May 2024.

[18] Nesij Ünal, Yahya Öz, and Tugrul Oktay. Conceptual design modeling by the novel aircraft conceptual design and analysis system (ACDAS). *Aircraft Engineering and Aerospace Technology*, 95(5):799–813, February 2023.

[19] Stephen A. Andrews and Ruben E. Perez. Comparison of box-wing and conventional aircraft mission performance using multidisciplinary analysis and optimization. *Aerospace Science and Technology*, 79:336–351, August 2018.

[20] J.L. Hess and A.M.O. Smith. Calculation of potential flow about arbitrary bodies. *Progress in Aerospace Sciences*, 8:1–138, 1967.

[21] Abbott, Ira H. and Von Doenhoff, Albert E. and Stivers, Louis S., Jr. . Summary of Airfoil Data. techreport TR-824, NACA, 1945.

[22] John L. Hess. *Calculation of Potential Flow About Arbitrary Three-Dimensional Lifting Bodies*. October 1972.

[23] N. Singh, S. Aikat, and B. C. Basu. Incompressible potential flow about complete aircraft configurations. *The Aeronautical Journal*, 93(929):335–343, November 1989.

[24] Tomasz Goetzendorf-Grabowski and Zdobysław Goraj. Calculations of stability derivatives of an aircraft using panel methods. *Transactions of Institute of Aviation*, 145(2):31–49, 1996. (in Polish).

[25] Paweł Błaszczyk, Tomasz Goetzendorf-Grabowski, and Zdobysław Goraj. Application of Panel Methods Into Computing the Selected Characteristics of Longitudinal Static Stability. *WUT Research Bulletin*, (7):75–80, 1997.

[26] Analytical Methods, Inc. MGAERO – Cartesian Grid Euler Method. `https://www.am-inc.com/MGAERO.html`, 2024. (Accessed on 01/05/2024).

[27] Ansys, Inc. Ansys Fluent - Fluid Simulation Software. `https://www.ansys.com/products/fluids/ansys-fluent`, 2024. (Accessed on 01/05/2024).

[28] Daniel P. Raymer. *Aircraft design: A Conceptual Approach*. AIAA education series. American Institute of Aeronautics and Astronautics, Inc., Reston, VA, sixth edition edition, 2018.

[29] R. Kaenel, A. Rizzi, J. Oppelstrup, T. Goetzendorf-Grabowski, M. Ghoreyshi, L. Cavagna, and A. Bérard. CEASIOM: Simulating Stability & Control with CFD/CSM in Aircraft Conceptual Design. In *28th Congress of the International Council of the Aeronautical Sciences, ICAS 2008*.

[30] J. Mieloszyk and T. Goetzendorf-Grabowski. Introduction of full flight dynamic stability constraints in aircraft multidisciplinary optimization. *Aerospace Science and Technology*, 68:252–260, September 2017.

[31] Jacek Mieloszyk, Tomasz Goetzendorf-Grabowski, and Dawid Mieszalski. Rapid geometry definition for multidisciplinary design and analysis of an aircraft. *Aviation*, 20(2):60–64, June 2016.

[32] Tomasz Goetzendorf-Grabowski and Tomasz Antoniewski. Three surface aircraft (tsa) configuration – flying qualities evaluation. *Aircraft Engineering and Aerospace Technology*, 88(2):277–284, March 2016.

[33] J. Mieloszyk, A. Tarnowski, A. Tomaszewski, and T. Goetzendorf-Grabowski. Validation of flight dynamic stability optimization constraints with flight tests. *Aerospace Science and Technology*, 106:106193, November 2020.

[34] Tomasz Goetzendorf-Grabowski and Zdobysław Goraj. Lateral stability of the canard configuration. *Journal of Theoretical and Applied Mechanics*, 25(1-2):47–61, 1987.