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MULTIDISCIPLINARY OPTIMISATION OF WING FOR CESAR AC-1 AIRCRAFT

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Abstract

The method for multidisciplinary and multi-objective optimisation, based on a genetic algorithm was presented. The generic parametric model of small aircraft wing geometry was developed. In this model a relatively small number of parameters describe wide class of wing geometries without and with high lift devices. The optimisation method used the objectives and constraints typical for aerodynamic design. Presented method was applied to design and optimisation of AC1 configuration (considered in CESAR project) turbulent wing. The results of the calculation have been discussed.

Key words: multi-criteria design, multidisciplinary design, genetic algorithm, aerodynamic of wing

INTRODUCTION

The costs of air transport small and medium-sized sequence distances are significantly greater than the costs of alternative modes of transport such as car and train. This is one of the major barriers limiting the potential for improving the competitiveness of this sector. Only to work on reducing the costs generated in the different phases of life cycle of aircrafts may be able to change this situation. The CESAR project (Cost-effective Small Aircraft) supported by the EU in 6 Frame Program was exactly focused on the development of technologies that reduce time to market entry and reducing the costs associated with this process for small aircraft. Basic aircraft configurations (Nae et all, 2006) were selected as demonstrators: AC1- low speed aircraft (turboprop) and AC2 – transonic speed very light business jet. In this study the results of work performed at the Institute of Aviation (Warsaw, Poland) in the development of numerical methods of wing design for a small aircraft will be presented. The proposed methodology is based on parametric modelling of complex aerodynamic objects (Stalewski, 2011), and numerical multi-criteria and multidisciplinary optimization taking account a various types of design constraints (Rokicki et al., 2009). The method has been used to design the turbulent wing for small aircraft. The result, related to AC2 configuration was discussed in the paper (Stalewski, Żółtak, 2011). In this paper research results concerning AC1 configuration are discussed.

DESIGN AND OPTIMISATION METHODOLOGY

Generally most of design and optimisation problems may be defined using three groups of parameters (Figure 1): (i) design variables defining geometrical parameters which may be changed in design process, (ii) environmental variables describing physical properties of the environment in which the designed object works, (iii) objectives and constrains defining expected properties of designed object.

A goal of the design is to find optimal set of design variables defining an optimal object i.e. the object for which the objectives reach possibly optimal values and which fulfils all constrains. To achieve the goal of design usually some "optimisation" tools are used. All of them can be collected in three sets (see Figure 1): the first set contains utilities dedicated to modification and parameterisation of a object geometry, including commercial CAD software and specialised codes realising parametric model of designed object, the second set contains optimisation method while the third set contains utilities dedicated to evaluation of objectives and constrains.

In presented problem the method for multi-objective optimisation based on a genetic algorithm was adapted to multidisciplinary design and optimisation of small aircraft. General scheme of applied methodology is shown in Figure 2.

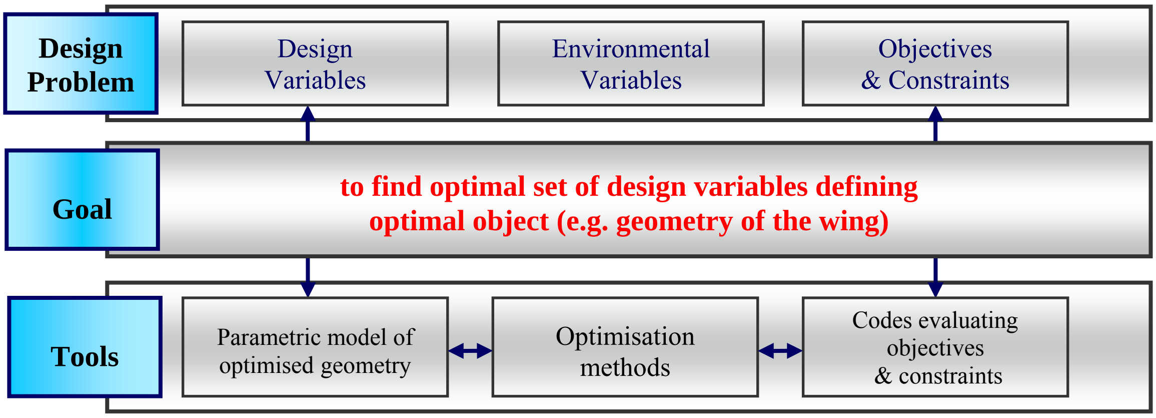

Figure 1 Scheme of solving a typical problem of parametric design and optimisation.

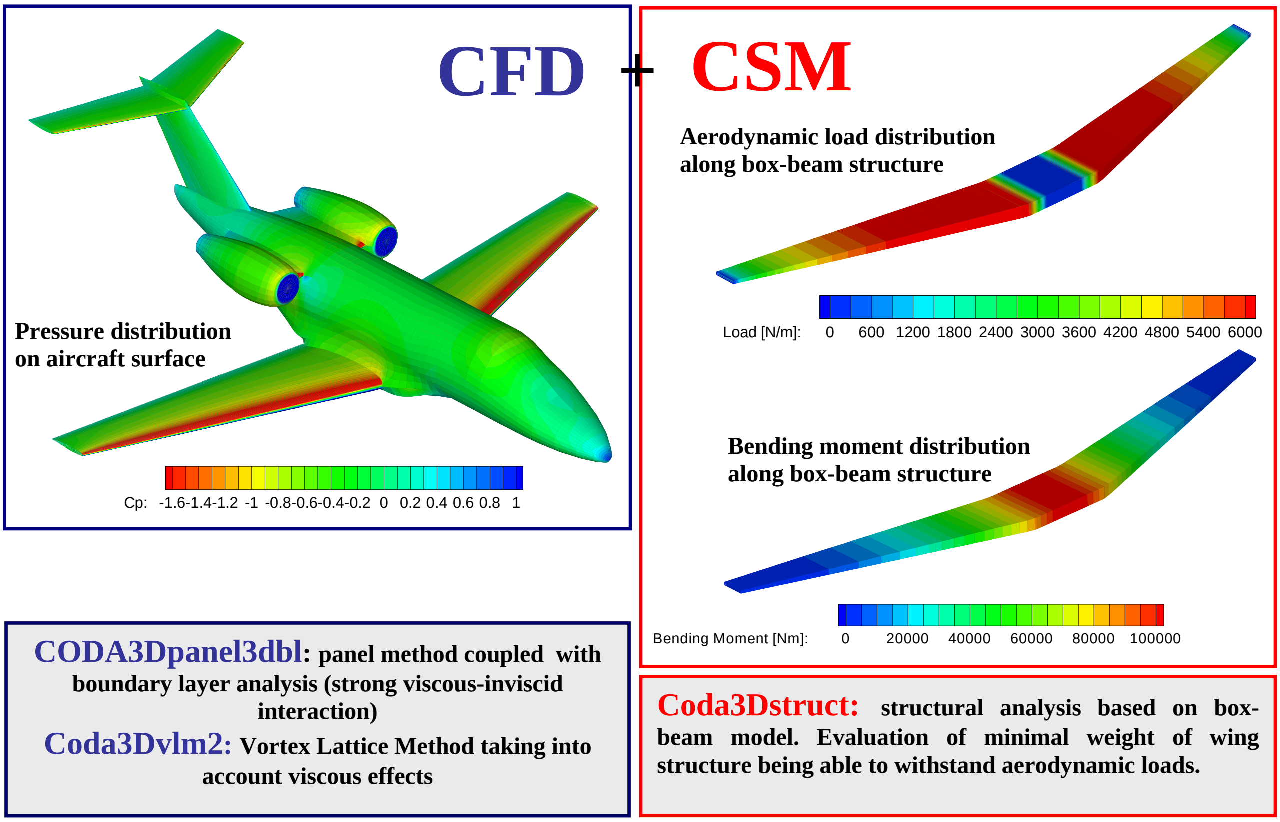

Figure 2 Scheme of simplified CFD and CSA codes used in turbulent-wing-optimisation process.

The generic parametric model based on in-house methodology (Stalewski, 2011) applied for small aircraft wing geometry was introduced. In this model a relatively small number of parameters describe wide class of wing geometries without and with high lift devices. NURBS (Non-Uniform Rational B-Splines) technique is used to geometry modelling and design space description. The optimisation method used the objectives and constraints typical for aerodynamic design. Besides quantitative objectives additional qualitative criteria were applied. The basic aerodynamic performance was determined using 3D panel method coupled with 2D boundary layer analysis (integral method) (Sznajder, Stalewski, 2010). Although the optimisation concerned just the wing, the aerodynamic computations were performed taking into account the whole aircraft. The box-beam model of the wing structure (Rokicki et all, 2009), was used to estimate a weight of the wing.

DESIGN AND OPTIMISATION OF AC1 TURBULENT WING

Presented above the multi-disciplinary, multi-objective optimisation method was used to design and optimise the AC1 turbulent wing for small aircraft defined in project CESAR. A designed wing should have fulfilled the requirements and constrains defined by other participants of project CESAR (Ancik, 2008).

Parameterisation of the wing

It was assumed that some parameters of wing planform would be fixed and some would be allowed to be changeable. The following wing planform parameters were considered as fixed: Root Chord (**RC**), area of Aileron Zone (**AZ**) and the line of rear spar position. The other wing planform parameters were assumed to be changeable during the design process.

It was considered that wing panels should have a classical, cost saving oriented manufacturability. It was assumed that the wing would consist of two segments (ruled surfaces): Flap Zone (**FZ**) and Aileron Zone. Considering possible degrees of freedom, three parameters were established as the design variables defining the wing planform. They were: Tip Chord, Mid Chord and wing area. Three end-sections of wing segments completely defined the wing surface: Root Section (**RS**), Mid Section (**MS**) which is the border section between **FZ** and **AZ** Flap and Tip Section (**TS**).

As a basic airfoil for designed, the ILL 5XX airfoil family was chosen (Wysocki et all 2007). Generally the ILL5XX airfoils in family having the same mean line and scalable distribution of thickness. Finally, (i) relative thickness, (ii) camber of mean line and (iii) twist angle were used to describe geometry in **RS**, **MS** and **TS** respectively. The twist angle of **RS** was established to 0 deg.

Besides the wing external shape, the wing box was also parameterised because its geometry was the input data for wing weight evaluations. Positions of spars were established at 10% and 60% of the wing chord for front and rear spar respectively. The rear spar was assumed to be perpendicular to the aircraft plane of symmetry.

According to the design of high lift system for airfoil ILL518 [3] (Wysocki et all 2007) it was assumed that within the **FZ** the designed wing would be equipped with Fowler Flap (**FF**). The chord of the flap was established to 30% of wing chord. Taking into account cost-saving-oriented manufacturability, it was assumed that the flap panel would be a ruled surface defined by its limiting cross sections. Generally the shapes of flap cross sections were assumed to be in accordance with the flap of the airfoil ILL518. So the shape of the flap was assumed as fixed. As a result, the problem of high-lift-system design and optimisation came down to search of optimal values of design parameters defining positions (gap and overlap) and deflections of **FF**p for both takeoff and landing configurations. The design of **FF** was performed independently after finishing the design process of clean wing.

Finally 11 and 5 design parameters were defined for design of clean wing and design of high lift system respectively.

Objectives and constraints

At the first stage of the design process, the clean wing was designed. It was achieved by solving appropriate multi-disciplinary, multi-objective optimization problem. The main goal of optimization was to design possibly low-drag and low-weight wing, having possibly high values of C_{Lmax}. Base on three following different flight conditions: two first (**FC1**, **FC2**) for cruise condition, last (**FC3**) for low speed (Ancik, 2007) the three objective functions $\mathbf{F_i}$ were established:

$$F_1 = \frac{L_1}{D_{w1}} \qquad F_2 = \frac{L_2}{W_{w2}} \qquad F_3 = C_{L\,max}$$

where: L_1 – lift of the aircraft for flight conditions FC1,
D_{W1} – drag of the wing for flight conditions FC1
L_2 – lift of the aircraft for flight conditions FC2
W_{W2} – minimal weight of the wing structure being able to withstand an aerodynamic load for flight conditions FC2
C_{Lmax} – maximum of C_L for flight conditions FC3

The main goal of optimisation was to maximise above objectives, that were evaluated using cost effective, simplified codes: (i) panel method coupled with boundary layer analysis (Sznajder, Stalewski, 2010), (ii) structural analysis based on box-beam model and (iii) Vortex Lattice Method taking into account viscous effects (Sznajder 2010).

After optimising a clean wing, an appropriate high lift system was designed. At beginning the shape of original high lift system (**FF**) of ILH518 airfoil (Wysocki et all 2007) was adopted to designed clean wing geometry. It was conducted using specialised in-house software. Next using Direct Optimisation method the position and deflection of **FF** was established. For each configuration, calculations of flow around complete aircraft were performed to assess expected value of C_{Lmax}. The calculations were performed using panel method (Sznajder, Stalewski, 2007) for the takeoff-and-landing **FC4**.

Results

Clean wing design

The multi-objective genetic algorithm was used to solve defined optimisation problem. Starting from a random population of optimized wings, the genetic algorithm generated subsequent generations of wings which were generally better and better fitted to design criteria. A population of each generation was constant and set to 48 individuals. The solution process was stopped after achieving the 300-th generation.

The solution of multi-objective-optimisation problem was the Pareto Set, including 1093 Pareto-optimal wings. From the Pareto Set the wing called AC1T-IoA-01 was down selected as the final version of designed turbulent wing for CESAR aircraft AC1. The values of objectives calculated for the wing AC1T-IoA-01 are presented in Figure 3, Figure 4 and Figure 5 and compared with objectives calculated for all obtained Pareto-optimal wings.

Geometry of wing AC1T-IoA-01 fulfils all geometrical constraints and preferences, particularly concerning cost saving oriented classical manufacturability. The wing AC1T-IoA-01 consists of two segments, corresponding to **FS** and **AZ**. The surface of each segment is a ruled surface, defined by its end-sections. Three basic wing sections (**RS**, **MS**, **TS**) were obtained by some modifications of basic airfoil ILL518. Spanwise distributions of sectional: relative thickness, camber of mean line and twist for the wing AC1T-IoA-01 are shown in Figure 6. The **RS**, **MS** and **TS** of the wing are shown in Figure 7.

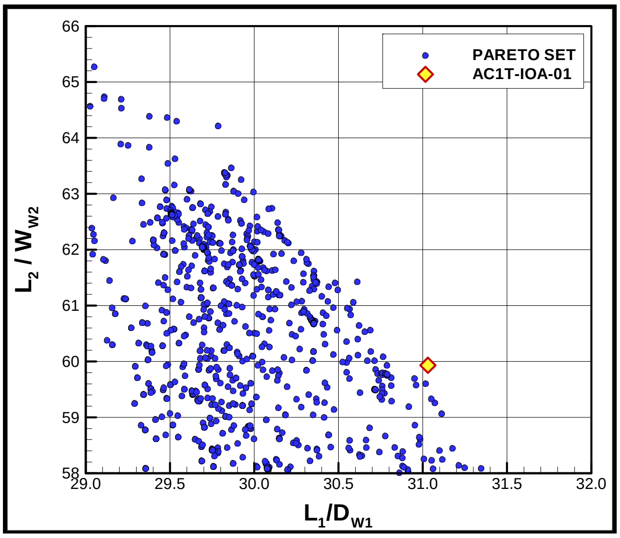

Figure 3. Projection of Pareto Set on F_1-F_2 space. AC1T-IOA-01 - selected "optimal" wing.

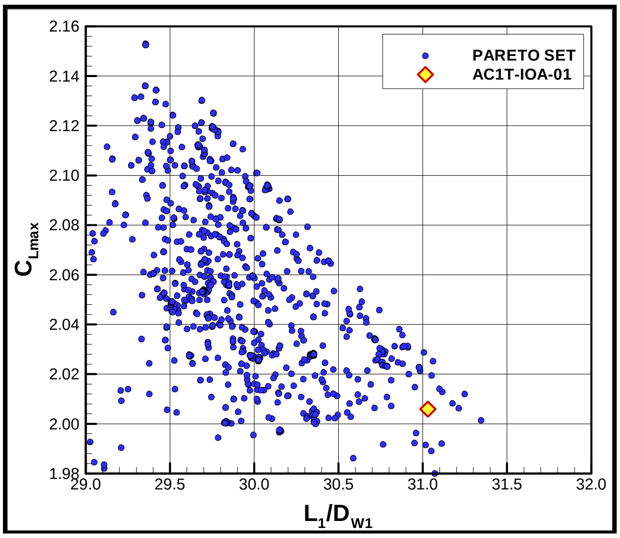

Figure 4. Projection of Pareto Set on F1-F3 space. AC1T-IOA-01 - selected "optimal" wing.

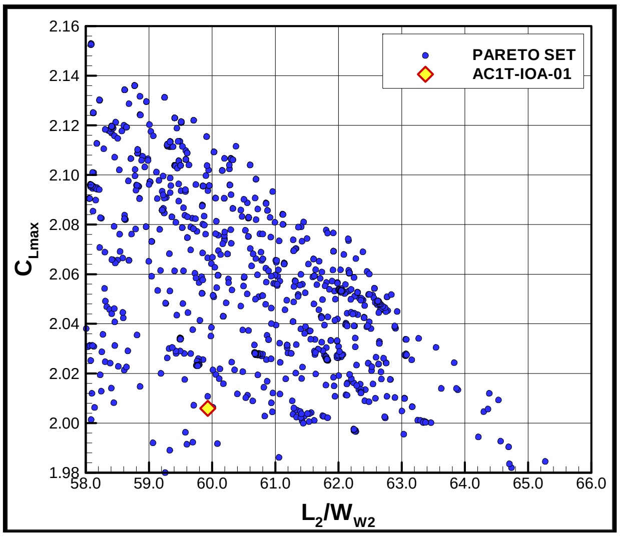

Figure 5. Projection of Pareto Set on F2-F3 space. AC1T-IOA-01 - selected "optimal" wing.

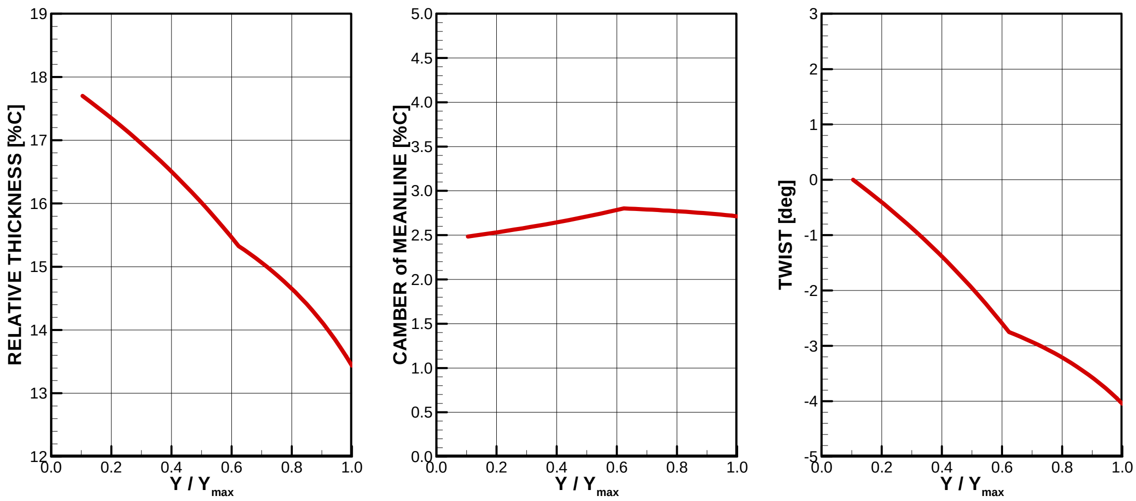

Figure 6. Geometry of the wing AC1T-IOA-01. Spanwise distributions of: relative thickness, camber of mean line and twist.

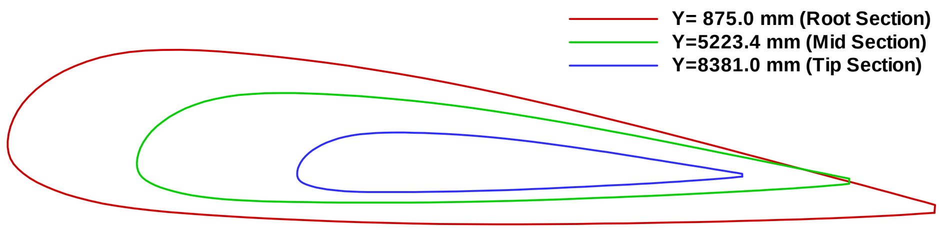

Figure 7. Root, Mid and Tip sections of the wing AC1T-IOA-01. Projection on aircraft plane of symmetry.

<u>Clean wing aerodynamic properties</u>

The main goal of optimisation was to design possibly low-drag and low-weight wing, having possibly high values of C_{Lmax}. To check whether the goal was achieved, a wide spectrum of aerodynamic characteristics for the wing AC1T-IoA-01 was analysed. The results of analysis were compared with aerodynamic properties of initially defined geometry called AC1T-BASELINE. All calculations were performed for complete aircraft configuration, although some analysed characteristics concerned only the wing. The Figure 8 shows wing drag polars calculated for wings AC1T-IoA-01 and AC1T-BASELINE. In the graph, a drag coefficient concerns only the drag of wing, but lift coefficient concerns the whole aircraft. The calculations were performed for full aircraft configuration, at cruise flight conditions **FC1**. At the design point the drag of compared wings is nearly the same, but for greater lift coefficients value wing AC1T-IoA-01 has reduced drag in comparison to wing AC1T-IOA-BASELINE.

According to (Ancik, 2007) the wing-design process should aim to fulfil the constraint concerning minimum pitching moment related to wing aerodynamics centre in cruise configuration **FC1**. The Figure 9 shows comparison of curves C_m versus C_L calculated at cruise flight conditions for wings AC1T-IoA-01 and AC1T-BASELINE. As can be seen, the wing AC1T-IoA-01 is characterised by considerably low negative pitching moment fulfilling above condition very well. Moreover, the pitching-moment characteristic of wing AC1T-IoA-01 favours the reduction of aircraft total drag, taking into consideration possible reduction of drag of horizontal tail.

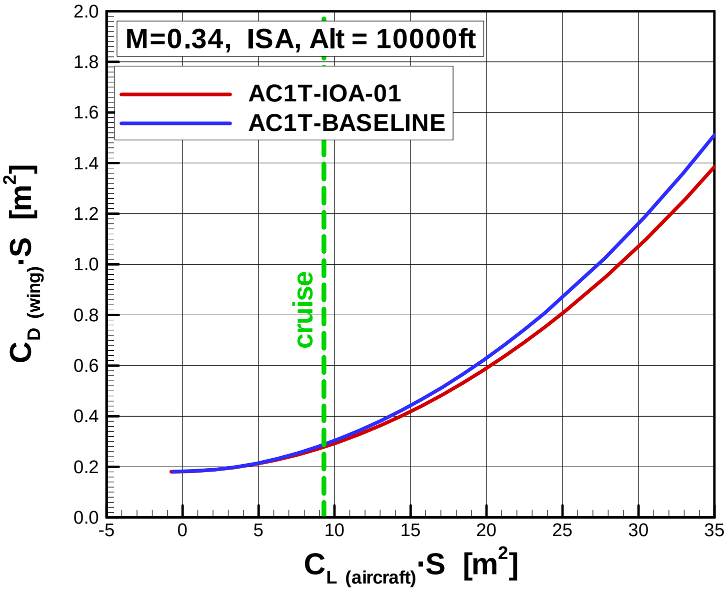

Figure 8. Comparison of wing drag polars calculated at cruise flight conditions **FC1** for wings AC1T-IoA-01 and AC1T-BASELINE

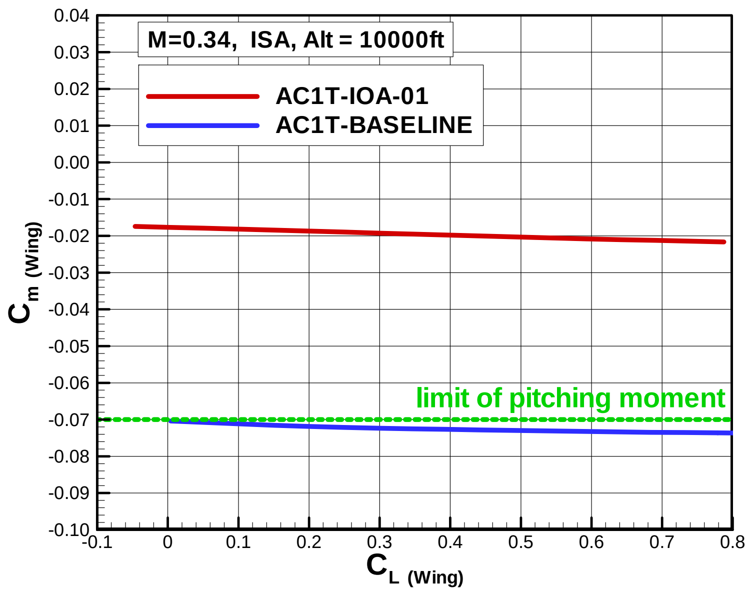

Figure 9. Comparison of curves C_m vs. C_L calculated at cruise flight conditions **FC1** for wings AC1T-IoA-01 and AC1T-BASELINE.

Figure 10 shows the comparison of curves C_L versus angle of attack α calculated for wings AC1T-IoA-01 and AC1T-BASELINE. Calculations were performed at flight conditions **FC3**. Presented lift coefficient concerns only an isolated wing but calculations were performed for complete aircraft. As can be seen, the optimized wing is characterized by slightly higher level of C_{Lmax} than baseline wing and then reference value of C_{Lmax} (Ancik, 2007).

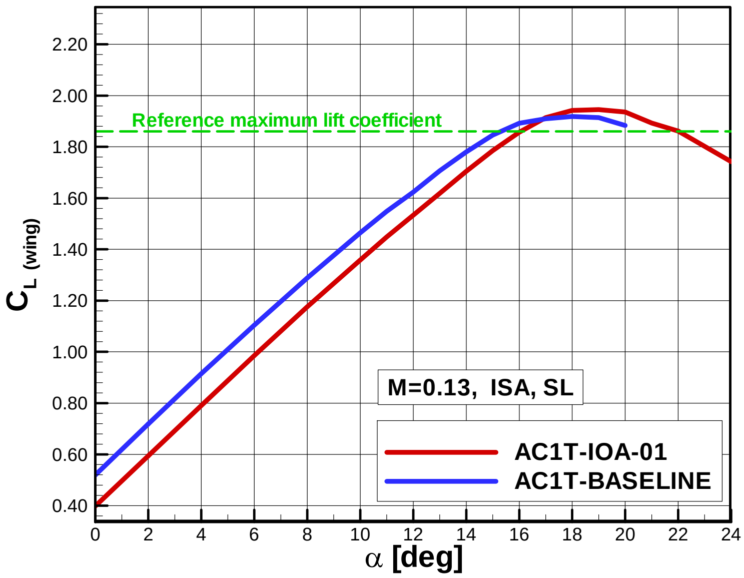

Figure 10. Comparison of curves C_L vs. α calculated for flight condition **FC3** for wings AC1T-IOA-01 and AC1T-BASELINE.

<u>Geometry wing with high lift system</u>

The **FZ** of wing AC1T-IoA-01 is limited by Flap-Inner Section (**FIS**) and Flap-Outer Section (**FOS**). Within the **FZ** the **FF** was designed. The chord of the flap equals 30% of wing chord. Taking into account cost-saving-oriented manufacturability, the surfaces of flap and main are ruled surfaces defined by their limiting cross sections. The limiting cross-sections of designed high lift system are shown in Figure 11.

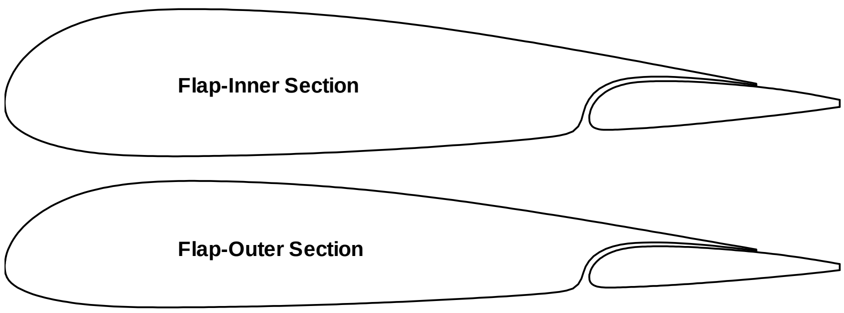

Figure 11. Flap-Inner and Flap-Outer Cross-sections of wing AC1T-IoA-01 with high lift system.

To define 3D position of deflected **FF**, the system of flap positioning was established. The system utilises positions of flap nose in two selected cross-sections: **FIS** and **FOS**. A way of positioning in given cross-section is explained in Figure 12. First the non-deflected **FF** moved to given position. For both **FIS** and **FOS** sections the shift is described by two parameters (ΔX,ΔZ) where: ΔX – is a distance between main-trailing-edge lower point and flap nose in direction parallel to the wing local chord in given cross-section, ΔZ – is a distance between main-trailing-edge lower point and flap nose in direction normal to the wing local chord in given cross-section. Next the flap is rotated by given deflection angle δ_{FL}. The rotation axis is simply the nose-line of the flap.

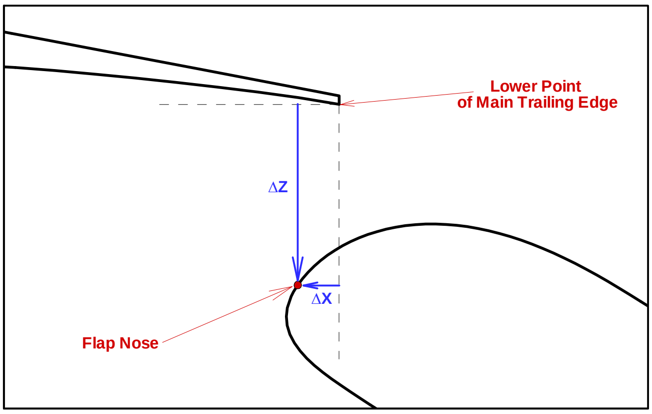

Figure 12. The definition of flap position in given wing cross-section.

The optimal position of flap for landing and take-off condition was obtained using Direct Method. **FIS** and **FOS** cross-sections of wing corresponding to optimal configuration are shown in Figure 14 and Figure 13.

Aerodynamic properties of high lift configurations

CFD calculations for high lift configurations of aircraft AC1 with wing AC1T-IoA-01 were performed using ***CODA3Dpanel3dbl*** code, for flight conditions **FC4.**

The Figure 15 presents dependence of lift coefficient C_L versus angle of attack α of complete aircraft for both takeoff and landing configuration. It important to note that optimal high lift configuration seems to be highly satisfactory in comparison with design criteria formulated in (Ancik, 2007). The resulting excess of maximal lift coefficient (of C_{Lmax}) was approximately 0.3 for landing and takeoff conditions.

CONCLUSIONS

The cost efficient methodology of aircraft / wing design and optimisation based on multi-objective and multi-disciplinary optimisation was developed and implemented. To improve efficiency of design process, a parametric model of AC1 aircraft/wing was worked out. Within the model both clean wing and wing with high lift system were parameterised.

The presented technique was applied to design a turbulent wing for AC1 concept of small aircraft considered in CESAR project. The final result of performed design process is the wing AC1T-IoA-01.

The high lift system (Fowler Flap) for the wing AC1T-IoA-01 was also designed. Using parametric model of the wing, positions and deflections of flap were optimised for takeoff and landing configuration.

The designed wing AC1T-IoI-01 together with its high lift system fulfils most of defined objectives and constraints. The wing AC1T-IoA-01 seems to be very interesting solution of turbulent wing for cost-effective, low-speed small aircraft.

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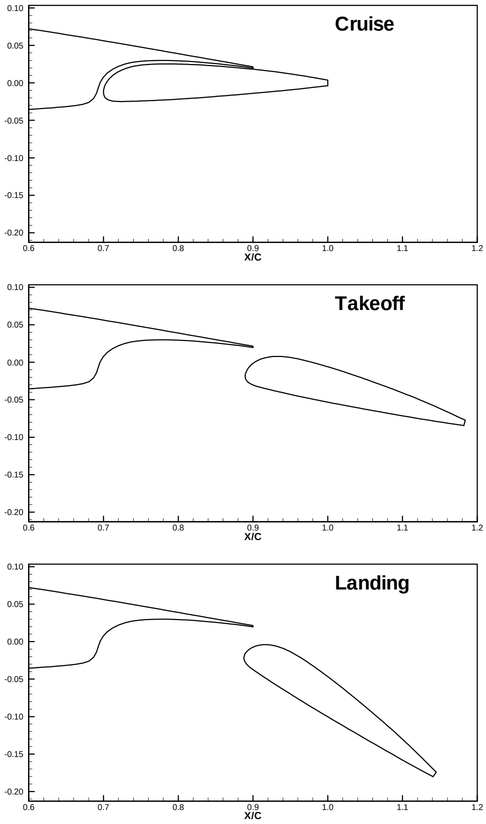

Figure 14. Optimised positions of Fowler flap in Flap-Outer cross-section.

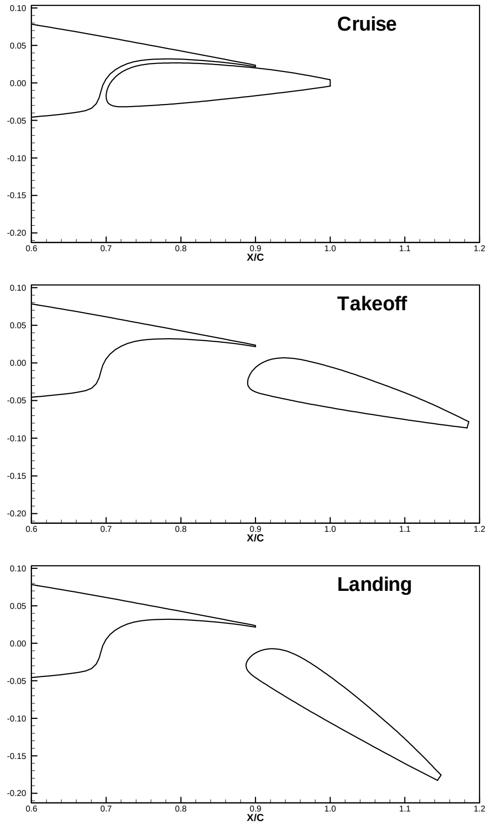

Figure 13. Optimised positions of Fowler flap in Flap-Inner cross-section.

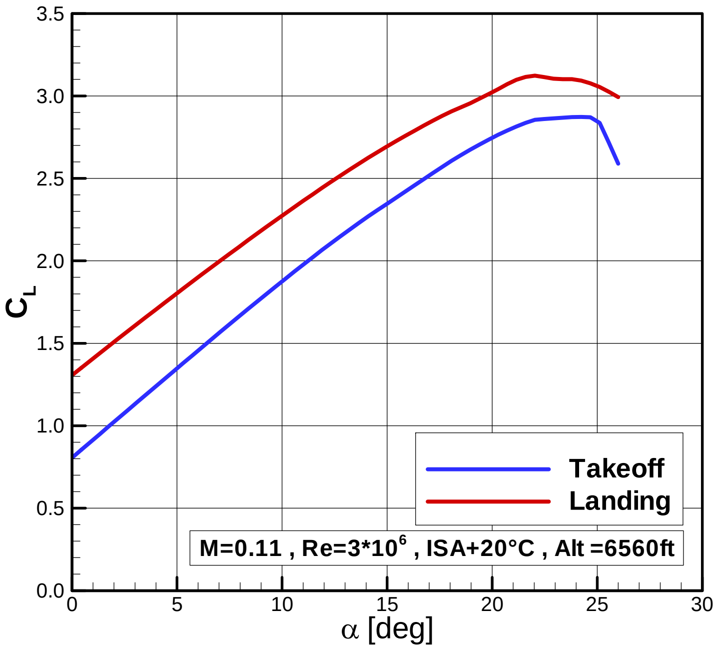

Figure 15. Calculated dependency C_L vs. α for takeoff and landing configuration of aircraft AC1 with wing AC1T-IoA-01 (**FC4** flight conditions).

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