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UNCONVENTIONAL CONFIGURATIONS - DESIGN AND OPTIMIZATION

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Abstract

Unconventional configurations can be very promising, but they need to be analyzed taking into account stability characteristics already in the preliminary stage of design. Paper presents a new approach to consider the flying qualities in the multidisciplinary optimization process. Examples of some unconventional configurations (canard, box wing, three surface, flying wing) are presented.

1 Introduction

Today aircrafts are close to excellence. The existing methods of design and optimization cause, that all characteristics are as good as possible. On the other hand, it causes, that if assumptions of a new project are similar, new designed aircraft will also be similar. Thus, today passenger airplanes are not recognized by common people and only experts are able to observe differences between these vehicles. This causes, that it is very difficult to design a competitive aircraft. Therefore, unconventional configurations seem to be very promising and attractive for engineers. They give a chance to design and build a competitive aircraft with the best performance ever seen.

The unconventional configurations can be very promising, but they also cause problems. The main problem are the flying qualities. Stability and control is the main problem of configurations such as canard, tandem-wing, three surface, flying wing, etc. (Fig.2) The question is how to combine high performance characteristics with satisfactory flying qualities. A good method to solve such a problem is to use an integrated environment for aircraft design. A good example is the idea of the SimSAC project [1] Fig.1 and the software package [2], developed within this project. However, design process and analyzes made in CEASIOM should be improved by optimization. Such approach was carried out and tested [3, 4] by authors, but the question of how to add stability criteria to multidisciplinary optimization was still open.

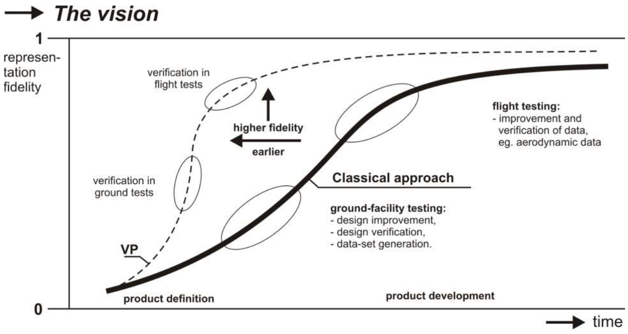

Fig. 1 The idea of cutting time by SimSAC

2 Flying qualities in optimization process

Optimization of the aerodynamic project of a new aircraft was described in numerous articles but new methods are still being developed, which is desired due to relatively high cost (time) of computation of the objective function. The cost increases by using the advanced CFD methods. It increases much more if we consider other disciplines like performance or stress analysis. The optimization tries to find the best solution, however there is no "the best stability" term in aircraft design. Only some stability criteria are de-

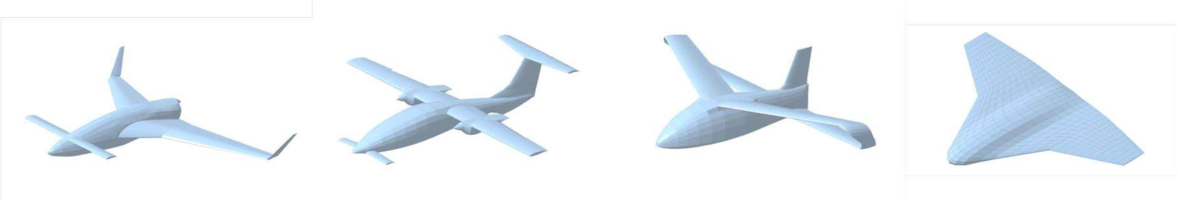

Fig. 2 Unconventional configurations.

fined, which must be met to satisfy the airworthiness requirements. Flying qualities are the result of aerodynamic project, mass breakdown, control surface design, control system, etc. and the idea is to translate the stability criteria to the constraints of optimization and use them in the multidisciplinary optimization process.

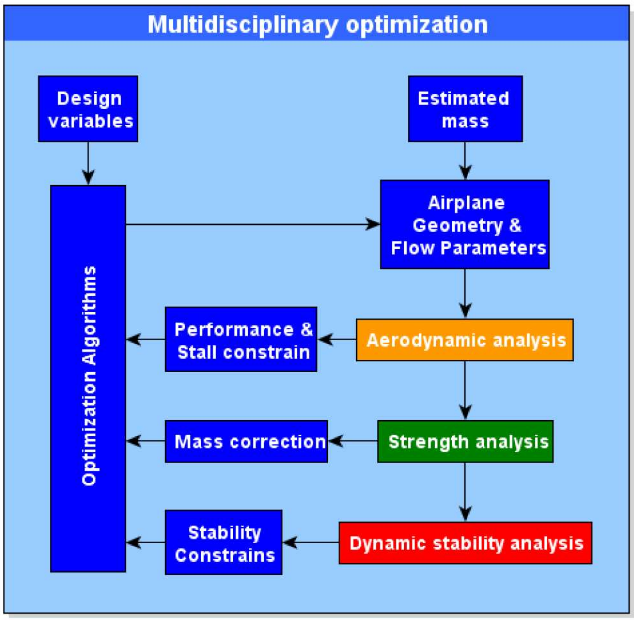

Fig. 3 Multidisciplinary optimization schema.

General schema of the numerical optimization applied by the authors is shown on Fig.3. The optimization process includes coupled simulations of aerodynamics [5], strength analysis and dynamic stability analysis. Aerodynamics influences performance characteristics and stall constraint for maximum lift coefficient. Results from aerodynamic analysis are also the input for strength analysis as loads and for dynamic analysis. Strength optimization gives mass correction of the structure for performance computation as well as for dynamic analysis. Dynamic analysis [6, 7] gives stability characteristics dependent on the flight conditions. Taking into account recommended criteria of handling qualities, stability constraints can be defined. Example of obtained optimization results for different airplanes is shown on Fig.4.

3 Unconventional configurations

Unconventional configuration is a real challenge for a designer. Usually potential advantages are connected with possible problems. In classical configuration the roles are separated. Wing gives the lift, fuselage is the place for payload, and the tail, horizontal and vertical, satisfies trim and stability. Very often horizontal tail and vertical tail is called a "stabilizer". The unconventional configurations are tailless (flying wing) or/and have additional surfaces on the front of the fuselage, which allow to increase the total lift but at the same time they decrease static margin and in consequence longitudinal stability is worse in comparison with conventional configuration. The lateral stability is also worsened due to shorter arm of vertical stabilizer or due to the lack of vertical surfaces.

3.1 Flying wing

The flying wing configuration seems to be the best from aerodynamics point of view. Clean lifting surface, without any disturbing elements, causes that parasite drag is minimized due to the smallest wetted area, however the aerodynamic effectiveness is limited. Lift has to be decreased by using a special airfoil shape, which gives relatively small pitching moment, in order to satisfy trim condition. On the other hand the wing must be swept to satisfy longitudinal and lateral stability, which results in worse lift to drag ratio in

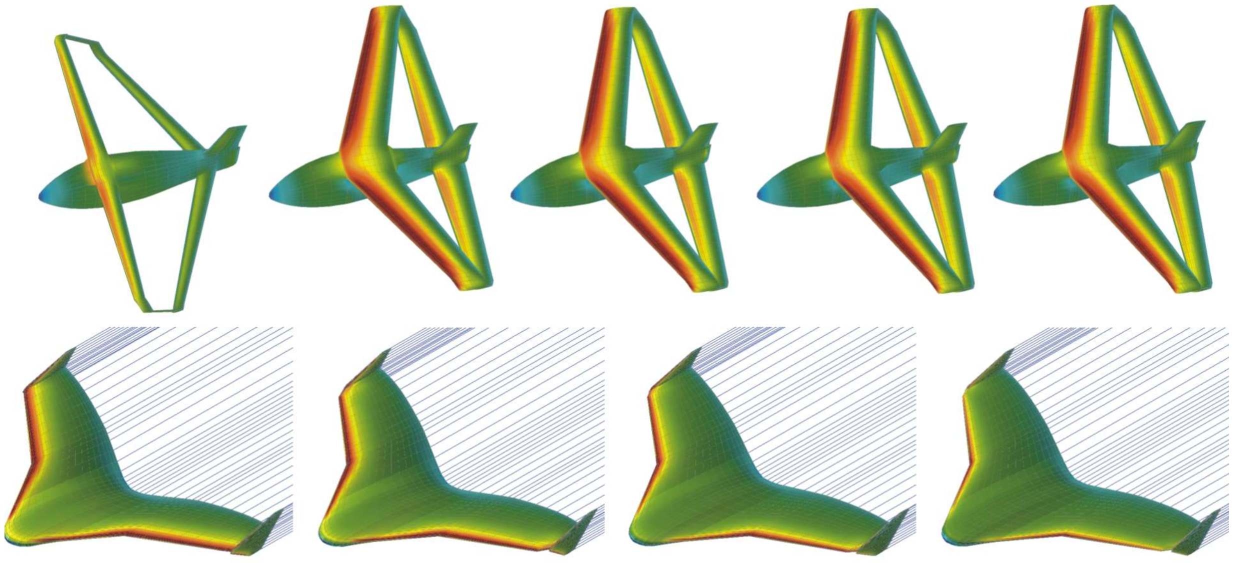

Fig. 4 Examples of the optimization improvement - Box wing and flying wing

comparison with unswept wing.

3.2 Canard configuration

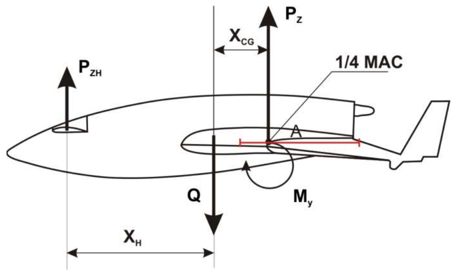

Fig. 5 Canard configuration.

The main advantage of canard configuration, often mentioned in numerous books and articles on aircraft design, is extra lift force acting on canard (forward wing) - Fig.5. However, the cost of such extra lift can be relatively high due to the downwash from canard acting on the main wing, which decreases its lift. The real problem of this configuration is stability. Usually trim conditions are contradicting the longitudinal stability. Forward position of center of gravity, necessary to satisfy sufficient static margin, needs high lift on the forward wing. On the other hand, high lift canard worsens stability. Additionally, designer must care about lateral stability [8], which could be insufficient due to the big part of fuselage on the front of the main wing and relatively short arm of vertical stabilizers.

3.3 Three surfaces configuration

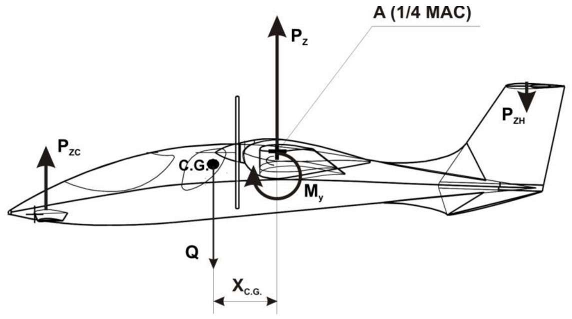

Fig. 6 Three surfaces configuration.

Three surfaces configuration (TSA) [9] connects characteristics of the canard and classical configuration. Thanks to the canard, the negative lift on the horizontal stabilizer is not significant. Small canard equipped with the effective flap allows to obtain relatively hight lift force necessary to satisfy trim conditions and classical horizontal tail increases static margin.

3.4 Box wing

Box wing has similar potential advantages as canard configuration, without the problem of horseshoe vortices disturbing flow on the main (rear) wing. Disadvantage include strongly coupled flow on the wing tips and high aerodynamic interference, which gives additional drag.

4 Design and Optimization - results

Paper presents examples of four different unconventional configurations. All presented configurations require careful analysis of flying qualities. In case of canard and three surfaces aircraft, multidimensional stability analysis was done. In case of flying wing and box wing, optimization procedures were applied, where flight stability criteria were included as constraints.

The problem of including the flight stability criteria in the numerical optimization was taken up by the research group in numerous projects. With time, the number of stability criteria and design variables increased significantly, leading to the numerical model, which mimics flight conditions very accurately.

4.1 Flying wing

A micro UAV was optimized as a flying wing configuration example. The UAV has unique propulsion system placement. The contra rotating propeller works in a slot placed in the middle of the wing. The objective was to minimize drag coefficient. The penalty function method was used to take into account two additional stability constraints. First constraint was the equilibrium condition of gravity force and lift force (1). Second constraint was to satisfy pitching moment derivative with respect to lift coefficient, which had to be equal to -0.1 (2). For a flying wing configuration, this sets the desired static stability margin. Complete objective function, which includes the penalty function constraints is described by equation (3). Drag coefficient in the objective function was multiplied by constant weight coefficient to increase its influence compared to the values of penalty functions.

$$P_1 = 0.5C_1^2/\mu;\;\; C_1 = mg - 0.5\rho V^2 S C_L \quad (1)$$

$$P_2 = 0.5C_2^2/\mu;\;\; C_2 = -0.1 - dC_m/dC_L \quad (2)$$

$$F_{objective} = 100C_D + P_1 + P_2 \quad (3)$$

The optimization task had seven design variables. Geometry of the fuselage part was already constrained due to the mission equipment size, but the wing's tip chord was an optimization variable. Wing's nonlinear twist distribution was controlled by three optimization variables, which generated fourth order polynomial Fig.8. Details of the geometry like wing tip shape, and wing's filet in the symmetry plane were also parameterized Fig.7.

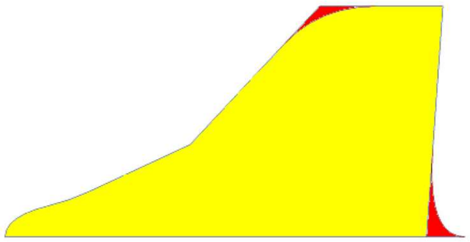

Fig. 7 Parameterized wing tip, and wing's filet marked with red color.

Mass of the aircraft was initially approximated, and stayed constant during the optimization. To achieve favorable longitudinal characteristics, center of gravity could move in a reasonable range achievable in practice. In the last design, environmental variable was equal to the value of angle of attack of the whole aircraft, which influenced aerodynamic coefficients. More details about the aircraft optimization can be found in [3, 10].

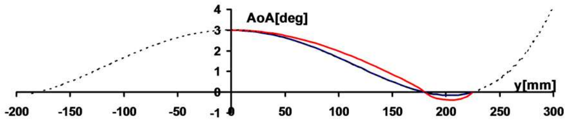

Fig. 8 Nonlinear wing twist distribution represented by 4th order polynomial.

As a result of the numerical optimization, aircraft configuration, geometry, position of center of gravity and cruise angle of attack were obtained. The aircraft was built and flight parameters were confirmed during test flight. For example, the proof of computations was zero deflection of flaperons for a trimmed aircraft, which has high nonlinear twist of the wing Fig.9.

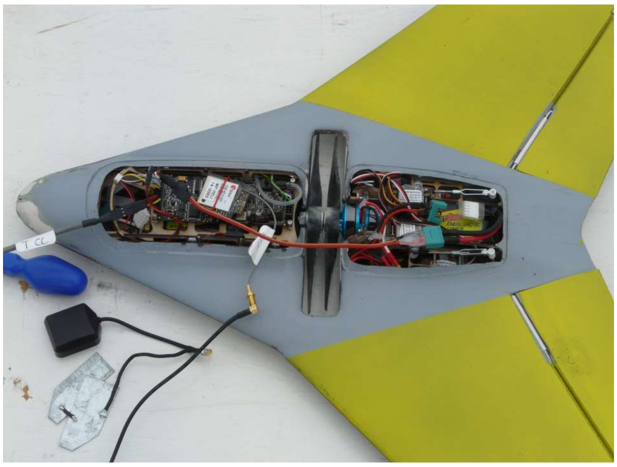

Fig. 9 UAV demonstrator, which confirmed good flying capabilities.

Optimization results were also confirmed with aerodynamic CFD simulations, and wind tunnel tests. Fig.10 shows comparison of airplane aerodynamic characteristics obtained from different methods. Computed optimum lies on aircraft's aerodynamic polar in a place where line going from the beginning of the coordinate system is tangent to the polar. This indicates, that the derived optimum of the aircraft coincides exactly with aircraft's maximum lift to drag ratio.

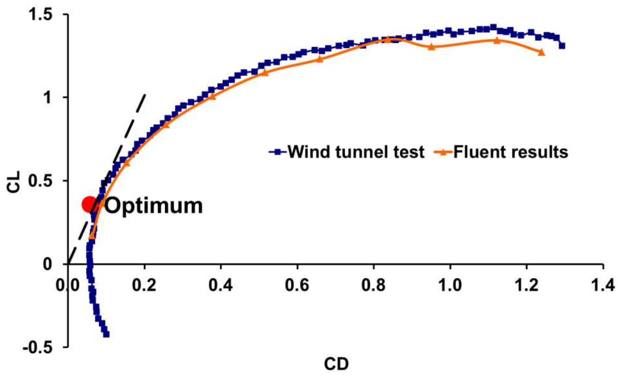

Fig. 10 Comparison of aircraft aerodynamic characteristics with obtained optimum.

4.2 Canard

The canard configuration chosen for analysis is a two-seat light aircraft (Fig.11), designed by authors.

The most important data is:

main wing span	7.0 m
canard span	3.6 m
body length	4.5 m
main wing area	6.6 m^2
canard area	1.28 m^2
mass	470 kg

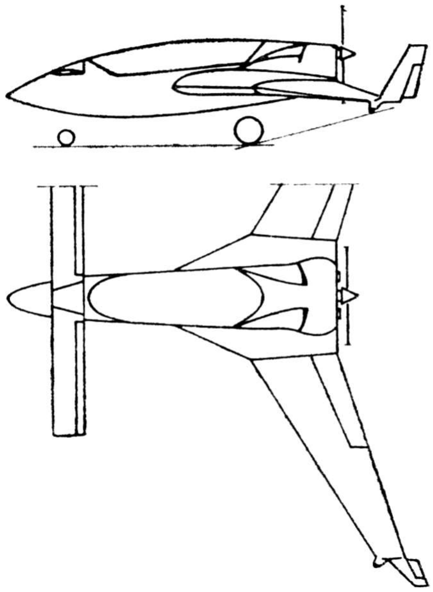

Fig. 11 Canard configuration aircraft.

Analysis of the configuration begun with estimation of the canard area and center of gravity to satisfy trim and static margin requirements. Next, dynamic analysis was done, taking into account four variables: vertical tail area (S_v), dihedral angle of main wing (G), and CG position (x and z).

The results of dynamic analysis have shown that for longitudinal stability, from four mentioned parameters, the most important are both coordinates of CG. In case of lateral modes the most important are: vertical position of the main wing with respect to the body, dihedral angle and vertical tail area. An increase of the dihedral angle, a decrease of the fin and rudder area as well as shifting the wing upward prolong the times to double of the Spiral mode, which is advantageous from stability point of view. Either a decrease of the dihedral angle when the fin and rudder area is constant or an increase of the fin and rudder area when the dihedral angle is constant can be compensated by shifting the main wing toward high-wing configuration.

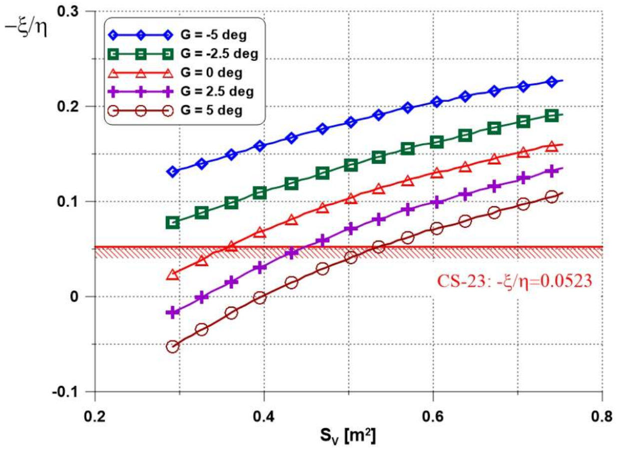

Fig. 12 Dutch roll characteristics versus vertical tail area and dihedral angle.

The Dutch Roll mode damping increases with an increase of the fin and rudder area as well as with a decrease of the dihedral angle (Fig.12). Shifting the mass center forward, improving the longitudinal static stability, slightly worsens the stability of the Dutch Roll mode increasing the time to half amplitude of an oscillation.

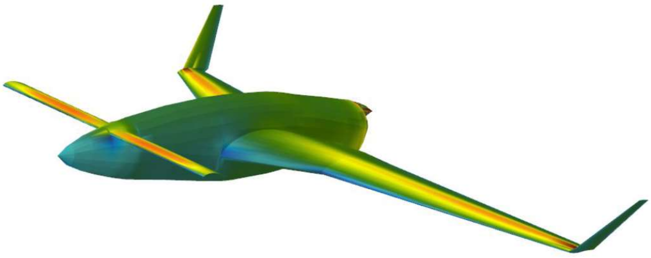

Fig. 13 Canard configuration - pressure distribution.

4.3 Three surfaces configuration

The next example is Three surfaces aircraft (TSA) [9]. Aircraft is equipped with Fowler flaps on the main wing and plain flap on the canard, which is coupled with the main flap. Elevator is situated classically on the horizontal tail. Such configuration allows to obtain high lift with small loads on the horizontal tail, thanks to the additional lift on the canard, which helps to compensate large pitching moment due to flaps.

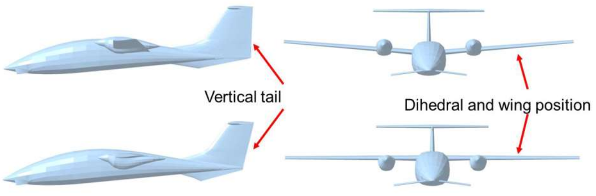

Fig. 14 Result of analysis - changes of configuration.

The analysis showed, that similarly as in case of canard configuration, the lateral modes require special attention. Fig.14 presents changes made within the design process as the result of dynamic stability analysis. Dihedral angle was decreased to zero and main wing was moved up to maintain the position of engines. An additional effect of decreasing the dihedral is that vertical tail area may be reduced, which also reduces the loads acting on the rear part of fuselage.

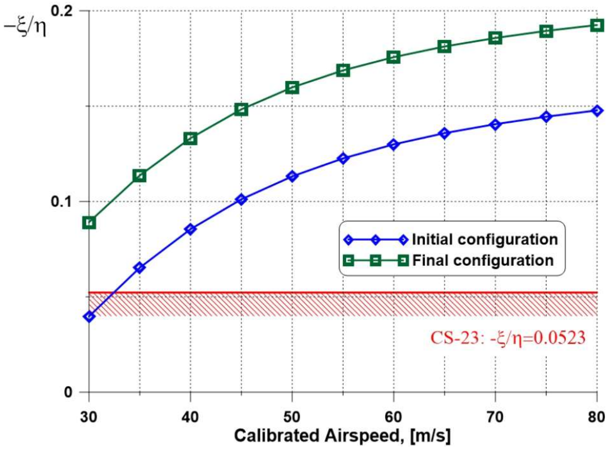

Fig. 15 Dutch roll characteristics against the background CS-23 criteria.

Fig.15 & 16 presents the Dutch roll characteristics before and after the change of the configuration. Figures show that for both criteria CS23 [11] and MIL-F-8785C [12] the characteristics are better and fully satisfy stability requirements.

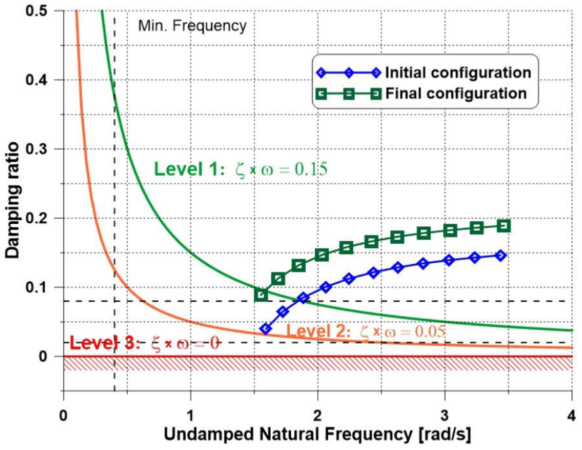

Fig. 16 Dutch roll characteristics against the background MIL-F-8785C criteria.

4.4 Box wing

The last example of numerical optimization with stability constraints is the most complicated one. The objective of the optimization was to obtain minimum power needed for cruise conditions (4), with a total number of 16 constraints. The numerical model coupled aerodynamic analysis, strength analysis, and dynamic stability analysis. Dynamic stability constraints satisfied the most comprehensive stability criteria available MIL [12], for different dynamic stability modes (5,6,7,8).

$$P_{min} = 0.5\rho\, V^3\, CD\; S \tag{4}$$

$$\zeta_{\;phugoid} > 0.04 \tag{5}$$

$$0.35 < \zeta_{\;short\;period} < 1.3 \tag{6}$$

$$\zeta_{\;Dutch\;roll} > 0.19 \wedge \omega_{\;Dutch\;roll} > 1 \tag{7}$$

$$T_{2\;spiral} > 20 \vee T_{2\;spiral} < 0 \tag{8}$$

During the optimization, 209 design variables were active. Global geometry of the aircraft was controlled by 24 variables, 183 variables controlled panel sets thickness distribution for strength analysis, and the last two were the angle of attack for the whole aircraft and position of the center of gravity.

Optimization history is shown on Fig.17. It is clear, that all the constraints, which were represented by penalty functions are equal to zero, while the power needed for cruise flight was minimized sufficiently. Finally obtained aircraft configuration is shown on Fig.18.

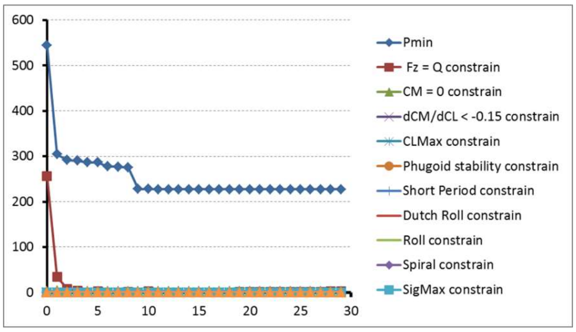

Fig. 17 Box wing aircraft optimization history.

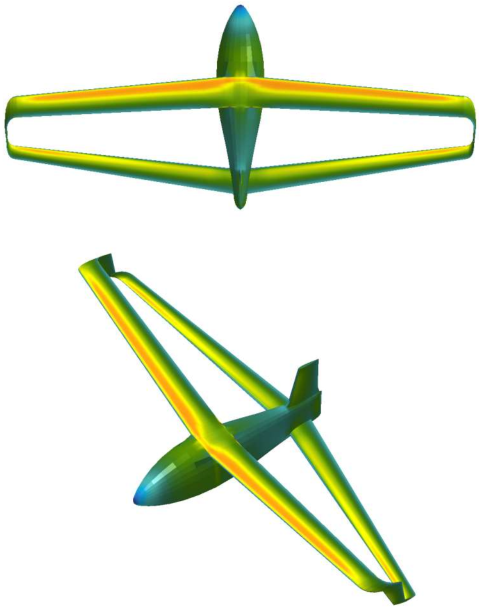

Fig. 18 Box wing aircraft configuration after optimization.

5 Concluding remarks

Unconventional configurations could be very promising but require special attention paid to flying qualities. Presented examples confirm, that MDO methods, which take stability criteria as design constraints, can be a very good tool within conceptual design level. It can reduce the cost of developing a new aircraft by minimizing the time and can prevent defeat.

References

[1] Rizzi. A.: Modeling and simulating aircraft stability and control-The SimSAC project, Volume 47, Issue 8, November 2011, Pages 573-588

[2] CEASIOM - Computerised Environment for Aircraft Synthesis and Integrated Optimisation, Methods, http://www.ceasiom.com/

[3] Mieloszyk J., HANDLING OPTIMIZATION PROBLEMS ON AN EXAMPLE OF MICRO UAV, Proceedings of the 3rd CEAS Air & Space Conference, 21st AIDAA Congress, Venice, 2011

[4] Goetzendorf-Grabowski T. Mieloszyk J., Mieszalski D., MADO - SOFTWARE PACKAGE FOR HIGH ORDER MULTIDISCIPLINARY AIRCRAFT DESIGN AND OPTIMIZATION Proceedings of 28th International Congress of the Aeronautical Sciences, Melbourne, 2012

[5] PANUKL potential solver, Software package, Warsaw University of Technology, http://www.meil.pw.edu.pl/add/ADD/Teaching/Software/PANUKL

[6] Goetzendorf-Grabowski T., Mieszalski D., Marcinkiewicz E., Stability analysis using SDSA tool, Progress in Aerospace Sciences, Volume 47, Issue 8, November 2011, Pages 636-646

[7] SDSA - Simulation and Dynamic Stability analysis, Software package, Warsaw University of Technology, http://www.meil.pw.edu.pl/add/ADD/Teaching/Software/SDSA

[8] Goetzendorf-Grabowski T., Goraj Z.: Lateral stability of the canard configuration, Journal of Theoretical and Applied Mechanics, Volume 25, Number 1/2, 1987, Pages 47-61

[9] Goetzendorf-Grabowski T., Antoniewski T., Three surface aircraft (TSA) configuration - flying qualities evaluation, Aircraft Engineering and Aerospace Technology: An International Journal, Vol. 88 Iss: 2, 2016, pp.277 - 284

[10] Raymer D.P., Enhancing Aircraft Conceptual Design Using Multidisciplinary Optimization Doctoral Thesis, 2002

[11] European Aviation Safety Agency (2012) Certification Specifications for Normal, Utility, Aerobatic, and Commuter Category Aeroplanes - CS-23, Amendment 3

[12] MIL-F-8785C - Military Specification Flying Qualities of Piloted Airplanes, 5 November 1980.

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